R E P O R T R E S U M E S

ED 003 572 56

MEASUREMENT AND ANALYSIS OF PHYSIOLOGICAL RESPONSE TO FILM.

BY- CASE, HARRY W. LEVONIAN, EDWARD
CALIFORNIA UNIV., LOS ANGELES

REPORT NUMBER NDEA-VIIA-458 PUB DATE DEC 62
REPORT NUMBER 62-66
GRANT OEG-704094
EDRS PRICE MF-$0.18 HC-$3.00 75P.

DESCRIPTORS- *FILMS, *MEASUREMENT TECHNIQUES, *PHYSIOLOGY, LOS ANGELES, CALIFORNIA, GALVANIC SKIN RESPONSE

THE PRIMARY OBJECTIVE OF THIS STUDY WAS THE DEVELOPMENT OF A SYSTEM WHICH WOULD ALLOW THE MEASUREMENT AND ANALYSIS OF PHYSIOLOGICAL RESPONSE OF STUDENTS VIEWING FILM MATERIAL UNDER CONVENTIONAL CLASSROOM CONDITIONS. THE GALVANIC SKIN RESPONSE (GSR) WAS MEASURED BY SENSORS AND USED AS AN INDICATOR OF STUDENT INTERACTION WITH THE FILM MATERIAL. IN THE TRIAL STUDY THE DIRECT RELATIONSHIP BETWEEN GSR AND TRAFFIC ACCIDENT INVOLVEMENT WAS INVESTIGATED. THE ADEQUACY OF THE SYSTEM WAS JUDGED SUFFICIENT BY THE INVESTIGATORS. (PM)

ED003572

458 458

U. S. DEPARTMENT OF HEALTH, EDUCATION AND WELFARE
Office of Education
This document has been reproduced exactly as received from the person or organization originating it. Points of view or opinions stated do not necessarily represent official Office of Education position or policy.

Measurement And Analysis Of Physiological Response To Film

Edward Levonian

Title VII Project Number 458
National Defense Education Act of 1958
Grant Number 704094

Principal Investigator: Harry W. Case
Co-Principal Investigator: Edward Levonian

University of California, Los Angeles
Report No. 62-66

The research reported herein was
supported by a grant from the
U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Office of Education

December 1962

MEASUREMENT AND ANALYSIS OF PHYSIOLOGICAL RESPONSE TO FILM

Edward Levonian

Title VII Project Number 458
National Defense Education Act of 1958
Grant Number 704094

Principal Investigator: Harry W. Case
Co-Principal Investigator: Edward Levonian

University of California, Los Angeles
Report No. 62-66

The research reported herein was
supported by a grant from the
U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Office of Education

December, 1962

Project Personnel

Principal Investigator	Harry W. Case
Co-Principal Investigator	Edward Levonian
Graduate Research Engineer	Joseph Aulenbrock
Graduate Research Biophysicist	Robert White
Graduate Research Psychologist	Marcia Winchester
Graduate Research Assistants	Stanley Azen Raymond Gregory
Senior Electronic Technician	David Kopfer
Engineering Aides	Richard Grayless James Tanenbaum
Secretary-Steno	Barbara Donner
Senior Typist-Clerk	Glenda McCoo
Typist-Clerk	Ann Bassin

Acknowledgements

Contributions have also been made by other persons not formally part of the project. In this regard, it is a pleasure to acknowledge the aid of Frederick H. Hollander, Associate Research Mathematician, A. Hurwitz, Graduate Research Mathematician, Michael Kaufman, Engineering Aide, all of UCLA, as well as the cooperation of Ron Coppin of the California Department of Motor Vehicles.

TABLE OF CONTENTS

		Page
I.	INTRODUCTION	1
	A. Problem	1
	B. Relation to Similar Studies	2
	C. Objectives	3
II.	MEASUREMENT OF PHYSIOLOGICAL RESPONSE TO FILM	5
	A. Measurement Considerations	5
	1. Appropriate Sensors	5
	2. Classroom Recording	13
	3. Multichannel Recording	15
	4. Data-Film Synchronization	16
	5. Computer Input	18
	B. Measurement Implementation	19
	1. Classroom	21
	2. Computing Facility	22
III.	ANALYSIS OF PHYSIOLOGICAL RESPONSE TO FILM	25
	A. Analysis Considerations	25
	1. Characteristics of the Pre-Sampled Signal	26
	2. Characteristics of the Sampled Signal	36
	3. Summary of Analysis Considerations	56
	B. Analysis Implementation	58
	1. Data Conditioning	58
	2. Data Analysis	60
IV.	A TRIAL STUDY	63
	A. Problem	63
	B. Method	63
	C. Results	66
	D. Discussion	67
	REFERENCES	69

I. INTRODUCTION

The project to be reported here involved the development of a system which should prove useful in educational film research. The system allows the measurement and analysis of physiological response of students viewing a motion picture (hereafter referred to as a film) in the classroom. It is expected that this system will allow an attack on research problems which involve film and which cannot be adequately investigated by procedures restricted to verbal response.

The system developed in this project should prove useful in both areas of research which involve films. The first area of research involves the investigation of some concept, such as emotion, learning, perception, attitude, intelligence, or personality, and in which the procedure involves audio-visual material presented by film. The second area of research involves the investigation of the effectiveness of film material. Since the procedure developed in this study constitutes a tool for both areas of research, no distinction will be made between these two areas of research in this report; both will be subsumed under "research involving film."

A. PROBLEM

Research involving film usually involves verbal response (oral or written) of subjects, despite the fact that there is usually little interest in the verbal response itself. The investigator is usually interested in some phenomenon, process, or behavior whose direct measurement is impossible or inconvenient. Verbal response is used as a simple and convenient measure of such a phenomenon, process, or behavior.

As such a measure, verbal response is more valid in certain situations than in others. While verbal response may be quite adequate where factual material is involved, verbal response may be less valid where unconscious factors or dissimulation can be expected to operate. In these latter situations, physiological response may prove to be more valid because it may reveal unconscious factors and dissimulation.

Aside from its possible greater validity, physiological response may be preferred for practical reasons. For instance, physiological response can be monitored throughout the film, whereas verbal response is usually obtainable only at discrete points in time, often only before and after the film. Further, the time relation between the film stimulus and the response may be desired, and this latency is more readily measured when the response is physiological or motor rather than verbal.

The problem is that no convenient system exists for measuring and analyzing physiological response to film presented under normal classroom conditions. The development of such a system was the goal of the current study.

B. RELATION TO SIMILAR STUDIES

Several studies have investigated physiological response to film.

Renshaw, Miller, and Marquis (1932; Renshaw 1932) measured the relation between movie attendance and sleep motility. The 163 subjects, who ranged in age from 6-19 years, saw 58 theatrical films. The results indicated that subjects at the age of puberty showed the greatest increase in sleep motility. Further, although females showed greater individual differences, males showed a greater increase in sleep motility.

Dysinger and Ruckmick (1933; Ruckmick, 1932) involved the measurement of galvanic skin response and heart rate during film viewing. The 150 subjects ranged in age from 6-50 years. The physiological responses were subjectively evaluated in relation to specific scenes and to subjects' essays. The results indicated that physiological reaction to film varies with age, sex, and film content, and that larger physiological reactions were recorded during those sequences for which the subject reported greatest interest.

Kleitman (1945) measured body temperature (as indicative of muscular tension) of two female subjects. Each subject had a temperature reading taken the day before, immediately after, and the day following film viewing. Each subject saw about 50 films. The results revealed a significant increase in body temperature immediately after the viewing of a film.

Humphrey (1950) measured GSR while individual students watched abstract movement on film, and a gross GSR score over the entire film was obtained. The 50 college students were also administered the ACE test, a measure of intelligence. The results indicated a significant correlation between GSR and ACE scores.

The current project involves the development of a system to measure and analyze physiological response to film in a manner quite different from the techniques employed in the above studies. The two primary differences are (1) simultaneous measurement of each student in the classroom viewing a film under naturalistic conditions, and (2) objective analysis of the physiological response to film.

C. OBJECTIVES

The primary objective was the development of a system which would allow the measurement and analysis of physiological response of students viewing film material under conventional classroom conditions. The system was conceived and developed as a unit within this one objective. For heuristic purposes, however, the measurement and analysis aspects will be discussed separately in Parts II and III of this report. Specific objectives will be mentioned within these major sections.

A secondary objective was to expose the system to a trial study. Such a study is described in Part IV of this report.

PRECEDING PAGE BLANK-NOT FILMED

II. MEASUREMENT OF PHYSIOLOGICAL RESPONSE TO FILM

The only type of measurement which will be discussed in this report will be quantitative measurement, and the adjective will be implied whenever the term measurement is used. Two types of quantitative measurements will be discussed: analog and digital. The physiological phenomenon is represented first as an analog measure, then as a digital measure, with all analyses being performed on digital measures.

Part II of this report is divided into two sections. The first section consists of a discussion of measurement considerations - problems involved in converting a physiological phenomenon to its digital representation in such a manner as to conveniently meet the objectives of the study. The second section describes measurement implementation - the measurement system as it exists currently.

A. MEASUREMENT CONSIDERATIONS

The measurement considerations revolved around five measurement requirements imposed by the objectives of the study (Levonian, 1962). These five requirements are listed separately.

1. Appropriate Sensors

The first requirement of the measurement system involved the availability of appropriate sensors. Sensors are devices which sense (or detect) the physiological phenomenon of interest. Very frequently sensors take the form of electrodes placed on the surface of the body. However, sensors need not be restricted to the outside of the body, nor need they necessarily touch the subject.

In general, sensors designed for clinical use are generally not appropriate for classroom use. Clinical sensors frequently encumber the subject, or impose a requirement on the subject which would embarrass him in a mixed group.

There are also practical limitations on the use of clinical sensors in classroom recording. Skin resistance sensors, for instance, often take

the form of two electrodes pressed against the palms. Electrode paste is generally used to enhance the electrode-skin contact. In classroom recording, however, the use of electrodes on both hands would make it awkward for the student to respond to a questionnaire while the film is in progress, and the use of electrode paste would be awkward to apply and to remove when many subjects are involved.

The major effort was concentrated on obtaining a skin resistance electrode appropriate for group use. Electrodes which did not require electrode paste were available from two commercial sources, but neither type of electrode proved satisfactory. The first type was a stainless steel fingertip electrode, with the electrode held against the palmar surface by a counter-force applied to the dorsal surface of the finger by means of a clamp adjusted by the subject. This model was rejected because (1) the contact area changed as the subject flexed his fingers, (2) the contact pressure was adjusted over too wide range by different subjects, and (3) the device was too large for small children.

The second type of commercially available electrode was also of stainless steel and designed to contact the finger at the palmar medial phalanges. Two stainless steel plates were forced together by a ¼" flat spring. The finger was inserted between the plates, with the spring extending over the tip of the finger. The plate on the palmar side was flat, while that on the dorsal side was curved. This model was rejected because (1) the contact area changed as the subject flexed his finger, (2) the electrodes weren't insulated, and electrodes on two fingers of the same hand could short, (3) the spring resulted in the electrical connection of the plates on palmar and dorsal surfaces, resulting in a reduction in sensitivity because of the conductance of the skin on the dorsal side, and (4) the device was too large for small children.

Since appropriate skin resistance sensors were not available commercially, and since there was little consensus of opinion regarding an adequate design (Auld, Dreyer, and Dollard, 1958; Blank and Finesinger

1946; Grings, 1953; Lykken, 1959), it was decided to design an electrode. Thirteen successive electrodes were designed, constructed, and rejected for one reason or another.

The first 7 electrodes utilized Velcro tape, a type of cloth manufactured in male and female parts, which when pressed together adhere in much the same way as a burr adheres to an animal's fur. The two bands can be pulled apart, then pressed together again as many times as desired. In the first 6 models the male and female bands were wrapped around the finger, adhering to each other on the dorsal side of the finger; in the 7th model the bands were wrapped around a Plexiglass ring.

A brief description is given of the 13 rejected designs in the order in which they were considered.

(1) Silver cloth electrode sewn to Velcro tape and conducting lead. Rejected because the cloth would rotate away from the palmar area of the fingertip.

(2) Silver cloth electrode 2" long sewn to Velcro tape and conducting lead; cloth would necessarily cover the palmar area despite rotation. Rejected because some subjects failed to wrap the Velcro tape tightly around the finger.

(3) Silver cloth electrode sewn to Velcro tape and conducting lead, with polyurethane pad (similar to foam rubber) cemented to Velcro tape at such a location that it would press against the dorsal part of the fingertip. Rejected because polyurethane foam didn't result in sufficient force to equalize the variations in the extent to which different subjects tightened the Velcro bands around their fingers.

(4) Silver cloth electrode sewn to Velcro tape and conducting lead, with Ensolite pad (similar to polyurethane foam but with superior compression properties) cemented to Velcro tape at such a location that it would press against the dorsal part of the fingertip. Rejected because an oxide from the positive electrode transferred to the finger tip, resulting in a condition which was cosmetically unpleasant.

(5) Stainless steel electrode curved to average finger, and riveted to Velcro tape, and with the conducting lead soldered to the electrode. Rejected because the electrode was too long, resulting in a change in contact area when fingers were flexed by those subjects who chose to place the electrode over both distal and medial phalanges.

(6) Stainless steel electrode (5 mil) curved to average finger and cemented to Velcro tape after the conducting lead had been soldered to the electrode. Rejected because some subjects failed to center the electrode over the palmar area.

(7) Stainless steel electrode (5 mil) soldered to a conducting lead, then cemented to an Ensolite pad cemented within a tubular Plexiglass ring worn on the fingertip; pushing against dorsal side of fingertip was another Ensolite pad cemented to a cradle which was pulled up against finger by strings, which were then secured by Velcro tape. Rejected because some subjects had difficulty in securing the strings.

(8) Stainless steel electrode (5 mil) cemented to an Ensolite pad cemented within a tubular Plexiglass ring. Design is same as above except that cradle pressure against dorsal side of fingertip is applied by means of a thumb screw. Rejected because of too great a variation in the pressure applied by different subjects.

(9) Stainless steel electrode (5 mil) soldered to a conducting lead, then cemented directly to a tubular Plexiglass ring worn over fingertip; diametrically opposite the electrode was cemented on Ensolite pad which pushed against the dorsal side of the finger. Rejected because a given inside diameter Plexiglass ring didn't fit a sufficiently large range of finger sizes.

(10) Stainless steel electrode (18 mil) soldered to conducting lead, then cemented to a polyurethane pad cemented inside a tubular Plexiglass ring; Ensolite pad pushed against dorsal side of finger. Rejected because polyurethane pad was insufficiently firm.

(11) Stainless steel electrode (18 mil) soldered to conducting lead, then cemented to a polyurethane pad within which was a coil spring of 29 mil music wire; Ensolite pad on opposite side of tubular Plexiglass ring pushed against dorsal side of finger. Rejected because spring pushed electrode so close to opposing Ensolite pad that subjects had difficulty in inserting fingers into opening.

(12) Stainless steel electrode (18 mil) soldered to conducting lead, then cemented to Ensolite cemented inside a tubular Plexiglass ring; another Ensolite pad pushed against dorsal side of finger. Rejected because conducting wire left the ring from one of its two faces, preventing the finger from being inserted from that side, thereby imposing an unnecessary constraint on the subject.

(13) Stainless steel electrode (18 mil), curved to fit palmar side of fingertip, soldered to conducting lead and cemented to an Ensolite pad cemented inside a tubular Plexiglass ring; another Ensolite pad cemented on opposite side of ring pushed against dorsal side of finger. Rejected because upper pad wasn't curved to conform to finger curvature, and because tubular ring wasn't tapered so as to be narrower at the electrode side.

The 14th model is the one currently in use. The electrode is made of the same stainless steel stock (18 mil) as used since the 10th model. The electrode is curved to fit the palmar surface of the distal phalange of either the first or third finger. The fanned out strands of the flexible conducting lead are soldered to the bottom of the electrode, after which the electrode is polished, then cemented to an Ensolite (Type M) pad. This pad rests in the narrow portion of a tubular transparent ring made of cellulose acetate butyrate (Plexiglass tends to crack when dropped on concrete). That portion of the ring which goes over the dorsal side of the finger extends from the tip of the finger to the first knuckle, whereas the opposite side of the ring is only half this length. This taper guarantees that the tubular ring will not touch the middle phalange if the subject flexes his finger, yet provides the

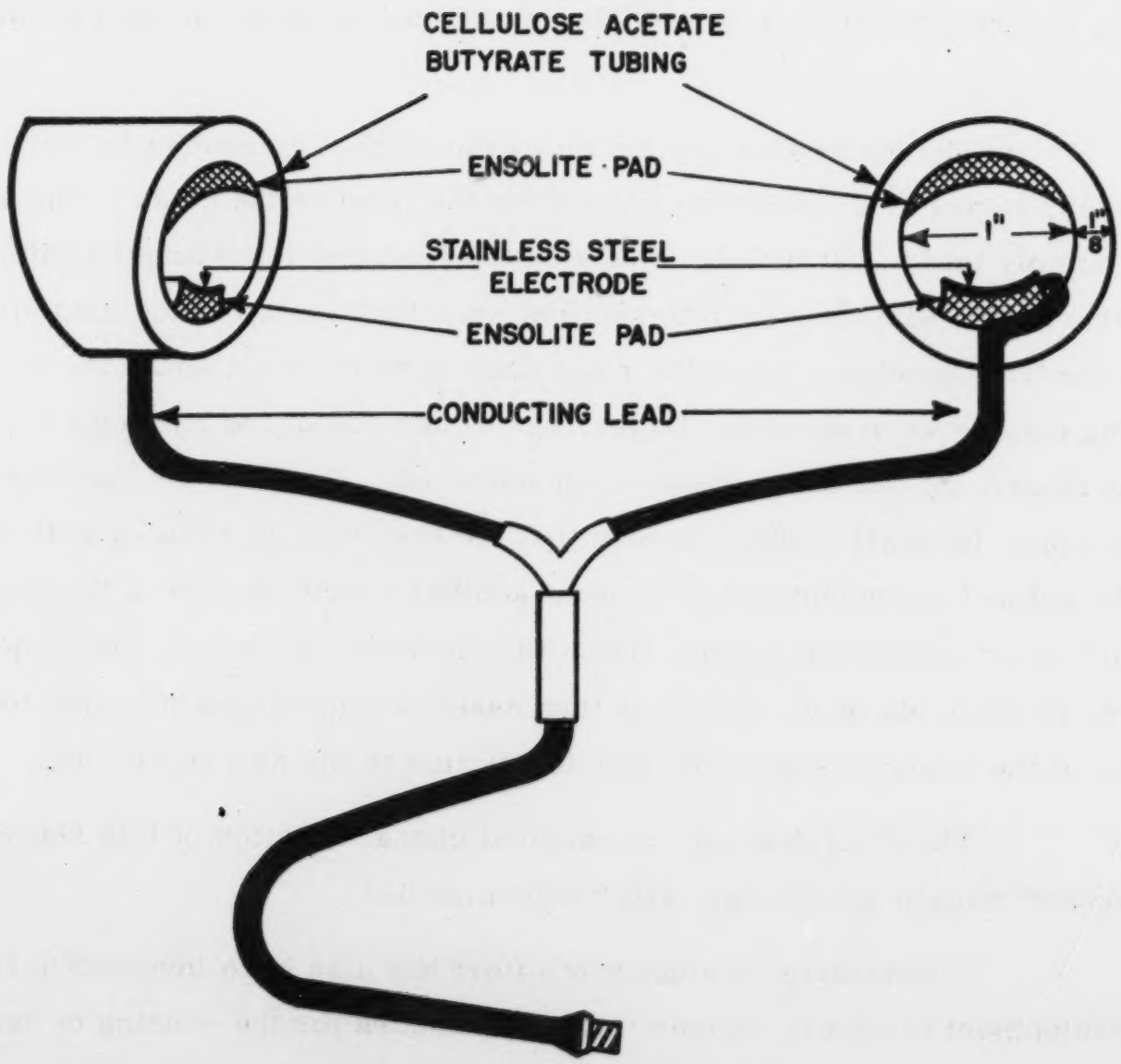
maximum area over the dorsal surface against which counter-pressure is applied. The conducting lead leaves the electrode at the side of the finger, and the free end of the lead is brought out through a hole in the bottom (narrow) side of the ring before the electrode pad and lead are cemented to the ring. An opposing Ensolite (Type M) cushion is cemented to the upper (wide) side of the ring. The assembly is shown in Figure 1.

The model is made in two sizes, and since each size can cover quite a range of fingers, the two sizes appear to cover the range from 5-year olds through large male adults. The smaller size uses a 3/8" square electrode, 3/16" thick cushions, and 3/4" inside diameter tubing (1" O.D.). The larger size uses a 1/2" square electrode, 5/16" thick cushions, and 1" inside diameter tubing (1 1/4" O.D.).

The conducting lead is cut to 3", and a 1" piece of spaghetti (Alpha Wire Co., FIT-275-12) is slipped over the free end. Then the two conducting leads are soldered to a coaxial cable, it being immaterial which of the two leads is soldered to the shield. Next, the two pieces of spaghetti are drawn over the joints and shrunk by heat application. The coax cable is cut to 6", and a 1" length of larger diameter spaghetti (Alpha Wire Co., FIT-275-8) is pulled over the two previously-shrunk pieces of spaghetti, as well as over the entire joint, and the outer piece of spaghetti is then shrunk. This configuration results in a strong joint with excellent strain relief properties.

The coax cable (Amphenol 21-598, RG-174/U) was selected after a number of heavier coaxial cables were tested under typical classroom situations. Amphenol 21-598 has an outside diameter of .100 inches, an impedance of 50 ohms, a DC resistance of .0018 ohms per foot, a capacitance of 29.5 micromicrofarads per foot, and a weight of about .0075 pounds per foot. This cable is used also as the transmission line from the student to the recording apparatus.

All connectors are Amphenol Series 27 Sub-Minax 50 ohm connectors. A 27-8 jack is soldered to the 6" length of coax, then crimped



SKIN RESISTANCE ELECTRODE
FIGURE 1

with an Amphenol Crimping Tool 227-900. The transmission cable is cut to 50 feet, and a 27-7 plug is soldered, then crimped to each end of the transmission line. Since both ends of this line have female connectors, either end may be used at the subject. A 27-9 bulkhead receptacle is screwed to the panel of the sampler, and the other end of the transmission line is connected to this receptacle, which has the same threads as the 27-8 jack.

The electrodes are put on by the subject according to instructions which, in practice, would be given from the front of the class. The subject is simply told to put the electrodes on the first and third finger (which are surprisingly similar in cross-section) such that the top of the ring slides up to the first knuckle. Since the rings may be worn on either hand, and either ring may be worn on either finger, and either end of the ring may receive the finger, no confusion has been encountered. Further, the curvature of the upper (dorsal) cushion is such that the electrode is radially self-centering. The subject is encouraged to request another electrode pair if the original pair is not comfortably snug. Once the electrode is seated, the subject is free to move his hand, and he is then asked to connect the 6" cable to the end of the transmission cable previously tied to the arm of his chair.

The electrical and mechanical characteristics of this sensor continue to remain satisfactory after extensive use.

A considerable amount of effort has also been invested in the development of equally simple fingertip sensors for the sensing of heart rate and finger temperature. These sensors and associated circuitry have been discussed in previous progress reports. While these sensors have been developed to the extent that quantitative measures of heart rate and finger temperature have been obtained, the sensors have not been developed to the extent that they can be incorporated into the same ring which holds the skin resistance sensor. There is every reason to believe, however, that this goal can be achieved with additional investment of effort.

2. Classroom Recording

The second requirement of the measurement system was that of classroom recording. Even though it was decided to obtain the physiological data in the naturalistic setting of the classroom, it was not immediately apparent whether the data should be transferred to the computer at the time of recording. Immediate real-time data transfer to a non-portable computer could be achieved by (1) transporting the students to a special classroom in close proximity to the computing facility and with direct connections to the computer, or (2) transmitting the data from the regular classroom to the computer facility by way of transmission lines or telemetering techniques.

The first possibility - that of transporting the students to a special classroom near the computing facility - was very appealing, for it allowed a single location for all data gathering. However, it had the disadvantages of presenting the student with a classroom different from his own, of requiring the transportation of the students to the classroom, and of requiring the coordinated scheduling of recording session and computer time. The second possibility - that of transmitting the data from the regular classroom to the computer - also had the disadvantage of requiring the coordinated scheduling of recording session and computer time. All these considerations argued against data transfer to the computer at the time of recording and argued for some method of information storage between transducer and computer. Further, the information should be stored in a form which is amenable to efficient transfer to a computer at any point in time after the recording.

One common method here is to record graphically, then convert to digital at a later time. However, such a method was never seriously considered, in part because of the expense and lack of portability of a graphic recorder with the necessary channel capacity, in part because of the inefficiency of converting electrical data to graphic form only to convert them back again to electrical form, but mainly because of the difficulty of retaining both accuracy and bandwidth when analog graphic records are time-sampled and converted to digital.

Another method of storing data for transfer later to a computer involves paper or card punching at the time of recording. The primary disadvantage of this method, so far as these film response studies are concerned, is its relatively slow recording rates. Paper or card punching is limited to about 1000 bits/second, which is considerably faster than graphic-to-digital conversion but too slow when the number of channels exceeds the conventional dozen or so.

Consider the recording capacity required for film studies. If each channel is sampled 24 times a second (once for every film frame), and each data sample is to have an accuracy of about 1%, then the binary recording capacity of each channel is nearly 200 bits/second. Quite obviously the total recording capacity necessary for classroom recording exceeds that of conventional paper and card punches. Such punches could be used if a buffer were employed between transducer and punch, but this did not seem warranted in view of the expense and technical problems involved. In addition to a slow recording rate, card punches have the additional disadvantage of not being readily transportable to the classroom, while paper punches, although portable, store data on a medium not usable for direct input to all computers.

Still a third method of storing data is on magnetic tape. Here the recording rate is limited primarily by the tape width, tape speed, and manner of recording and reproduction. A recording capacity suitable for classroom research is readily achieved by conventional instrumentation tape recorders. Further, some of these recorders are portable. Thus, it was decided to use a magnetic tape recorder because of its recording rate and portability.

The decision to utilize magnetic recording did not dictate the mode of recording - whether direct, digital, FM, etc. Direct recording was eliminated immediately as a possibility because of its inability to record DC.

Digital recording requires analog-to-digital conversion in the classroom. While such a converter may be portable, its use at the time of recording would simply confound the primary problems involved in group measurement. Therefore, digital recording was not used initially, but this method of recording will also be evaluated after a greater appreciation is gained of the problems unique to classroom recording.

A third mode of recording is FM. Frequency modulation requires voltage-to-frequency conversion in the classroom. Such a converter is usually portable, and, in fact, is usually an integral part of FM recorders. Further, FM allows the recording of DC, and has sufficient accuracy and bandwidth to handle the measurement requirements. Such considerations resulted in the choice of FM recording for the film response system.

3. Multichannel Recording

The third requirement of the measurement system involved the retention of data in such a form that the data from each sensor could be identified and analyzed as a unit. In effect, this required as many recording channels as the product of the number of student times the number of sensors per student. The number of students would range from a seminar group to an audience in a lecture hall, while the number of sensors per student would range from one to several. Thus, the measurement system should have at least 100 channels, preferably several hundred. The problem, then, involved the manner in which at least 100 channels should be handled by the portable FM magnetic tape recorder.

Standard tape widths for magnetic tape recorders are 1/4 inch, 1/2 inch, 1 inch, and 2 inches. Recorders which accept the wider tapes can handle a greater number of tracks, but, at the same time, such recorders are less portable: one must trade tracks for portability. A 1/2 inch recorder seemed an acceptable compromise for the measurement system being discussed. Recorders which handle 1/2 inch tape usually have 7 tracks. The distinction which is being made between "channel" and "track" deserves

emphasis: a "channel" is associated with the data from a sensor, while a "track" is associated with a recorder head.

The problem discussed now involves the recording of at least 100 channels on 7 tracks. The two most common methods of multiplexing several channels on a single track are frequency-multiplexing and time-multiplexing. The adjectives refer to the parameter which enables separation of the several channels. In frequency-multiplexing, each channel has its own carrier frequency if amplitude modulation is used, or its own center frequency if frequency modulation is used. In time-multiplexing, each channel is recorded successively in time. For either type of multiplexing, the several channels on a given track must be separated before data analysis is undertaken. The separation procedure involves frequency discrimination to separate frequency-multiplexed channels, or time discrimination to separate time-multiplexed channels.

In deciding which of these two basic methods would be most appropriate for the measurement system, the characteristics of each were kept in mind: frequency-multiplexing allows the use of continuous recording, while time-multiplexing allows the use of simpler equipment. It might appear at first that continuous recording is ideally suited to the inherently continuous characteristic of most psychophysiological phenomena. However, if the data are to be analyzed by numerical methods, then each channel must be sampled at some time before analysis. Thus, when numerical analysis is employed, continuous recording serves only the function of delaying the time at which sampling is undertaken. Because numerical analysis would be used in the measurement system, a decision was made to use the simpler time-multiplexing method of multichannel recording.

4. Data-Film Synchronization

The fourth requirement of the measurement system was the provision that the data be synchronized with the motion picture film. Such synchronization would then allow (1) the determination of the point in the film corresponding to a given point in the data, or (2) the determination of

the point in the data corresponding to a given point in the film. Both determinations would be useful in establishing stimulus-response relations.

Corresponding points in data and film could be specified by one of three methods: (1) both data and film points could be referred to a common dimension, (2) data points could be referred to some film dimension, or (3) film points could be referred to a data dimension. With regard to reference dimensions, the best common dimension is undoubtedly time, a good film dimension is lineal distance, and an adequate data dimension depends on one's research orientation. Since there is virtually no disagreement over the adequacy of time or distance references, only these two were considered in the design of the measurement system.

Consideration was given first to the possibility of referring data points and lineal film distance to a common time reference. Time identification of data points is commonly used and not particularly difficult. However, time identification of lineal film distance is difficult because of the manner in which the typical 16 mm film projector (the type used in the system) is constructed. The film transport speed of the conventional projector is generally influenced by line frequency, governor setting, reel size, etc., resulting in a film speed which bears no simple relation to chronological time. Under these conditions, the time indexing of lineal film distance would require the recording of the time integration of film transport speed. Such recording not only introduces design problems but also reduces the number of channels available for data recording.

Consideration was given next to the possibility of referring data points to lineal film distance. The problem here is to identify each data point with a film point (a point along the lineal dimension of the film). This can be achieved by time-sampling the continuous data at a rate which bears a fixed relation to film units, frames for instance. For example, assume that each analog signal is sampled once per frame, then the 412th data point corresponds to the 412th frame, both taken from the same origin. The relative simplicity of referring data points to film points resulted in the adoption of this method for synchronizing data and film.

5. Computer Input

The last requirement imposed on the measurement system was that it allow efficient computer input of the data. Data are usually transferred to a computer from records which store the data in punched form (as with punched tape or cards) or in electrical form (as with magnetic tape or discs).

Consideration was given first to the feasibility of transferring the data to the computer from a punched source, say cards. As has been described, the data are recorded on magnetic tape, and card input to the computer would require that the data on magnetic tape be punched onto cards. Previously, it was stated that bufferless card punching was not sufficiently fast for real-time recording, but card punching at a time after recording need not be restricted to a time duration equal to the length of time to make the recording. Hence, card punching after recording is feasible and was considered in the design of the system.

The number of cards which would result became an important factor. Consider the case of 100 channels, each sampled 24 times per second (the number of film frames/second at sound speed). One minute of recording would result in 144,000 data points. If each data value is to have 1% accuracy, two decimal digits or seven binary digits are required. One IBM card could contain 40 data points in decimal, or about three times as many data points in binary. It would require about three boxes of decimal cards or one box of binary cards for each minute of record. Further, a considerable amount of time would be required to punch these cards and to read them later as the information from them were transferred to a computer or to digital tape. Problems with punched tape are similar in nature. All in all, data transfer to the computer by means of punched cards or tape did not seem very desirable.

Consideration was given then to the feasibility of transferring the data to the computer from an electrical source. Since it had been decided already to record the data on magnetic tape, the use of this record as the

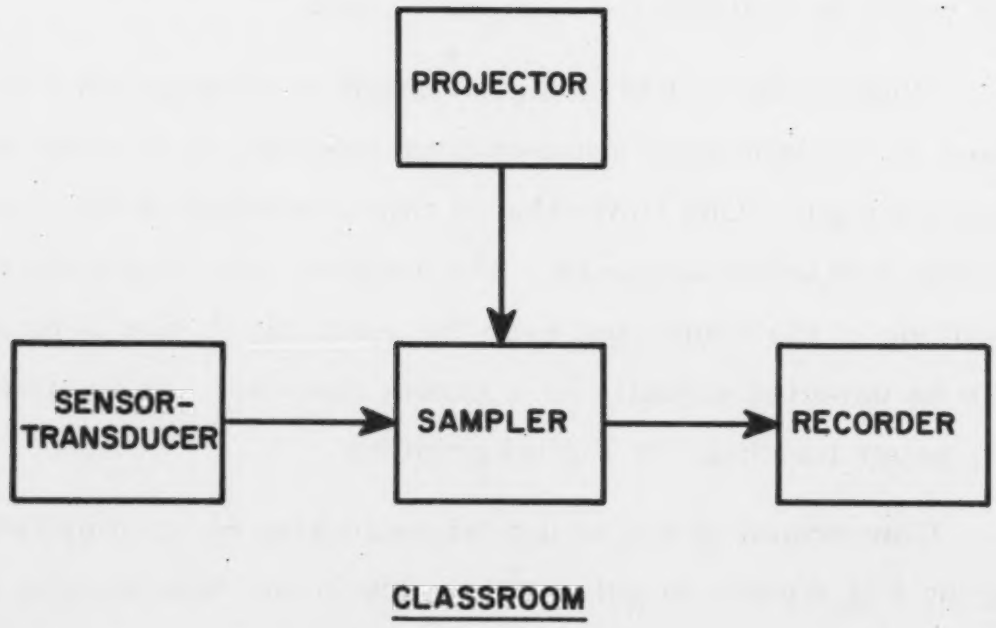
electrical source was considered. The design up to this point had determined essentially the characteristics of this electrical source: continuous data would be time-sampled, and several channels would be recorded in FM on a single track. The data in this form would have to be converted to digital before it would be suitable for computer input.

Conversion of FM to digital could be accomplished by counting the FM pulses on the tape over a known time interval, then using the total count for computer input. One limitation of this procedure is the readout rate of conventional frequency counters. The readout rate is usually a function of the magnitude of the count, but even the most rapid rate is made to be slow enough to be detected visually by a human observer, or to operate card punches, paper punches, or digital printers.

Conversion of FM to digital could also be accomplished by transforming the FM signals to pulse-amplitude form, then feeding these pulses to an analog-to-digital converter. Most FM tape recorders are in actuality recorder-reproducers with integral discriminators, thus providing a ready conversion of the sampled data in pulse frequency modulation to pulse amplitude modulation. Further, analog-to-digital converters typically have readout rates of between 2,000 to 20,000 conversions/second, at least two orders of magnitude faster than the procedure discussed in the preceding paragraph. There seemed little doubt that the procedure of this paragraph should be utilized in the measurement system.

B. MEASUREMENT IMPLEMENTATION

The previous section discussed design considerations of a measurement system which would allow for appropriate sensors, classroom recording, multichannel recording, data-film synchronization, and computer input. These measurement considerations have been implemented, and this section will contain a brief description of the measurement system as it now exists. This measurement system is diagrammed in block form in Figure 2, which shows the system as existing in part in the classroom, and in part in the computing facility.



MEASUREMENT SYSTEM
FIGURE 2

1. Classroom

In the upper half of Figure 2, one of 180 possible lines is shown as the input to the sampler. These 180 lines can carry 180 signals from one subject, or one signal from 180 subjects, or any combination not exceeding 180. The origin of the input signal to the measurement system will depend on the particular physiological variable being measured. By way of example, the manner of obtaining signals representing skin resistance will be described.

A constant current source is placed across the output of the sampler in such a way that current flows through the subject's skin only when the sampler switch is closed (roughly 3 microamps for 1 millisecond duration repeated 24 times a second, conditions which minimize polarization problems). The height of the resulting pulse is proportional to the skin resistance. The pulses are adjusted in height before recording such that the pulse representing the highest expected value of skin resistance is equal to the full range of the tape recorder, which is also equal to the full range of the analog-to-digital converter. On every run, calibration data are recorded on one signal channel.

The sampler is a six-pole rotary commutator (General Devices, Model 102A-2), with 30 break-before-make contacts/pole. This commutator is driven by a receiver synchro, the transmitter synchro for which is driven by a standard 16 mm projector. Electrical rather than mechanical coupling of projector and commutator permits independent placement of these two components. This linkage guarantees a stimulus-response relationship to about one millisecond; that is, for any instant of stimulus presentation, the response is known to within 1 ms. of that instant.

Synchronization is such that the commutator rotates at half the film transport speed. Since this speed is about 24 frames/second, the commutator rotates at about 12 rps, making 12 the minimum sampling frequency

(rate) for each channel. However, the effective sampling frequency can be decreased to any desired value by discarding data in the computer, or the sampling frequency can be increased by multiples of 12 up to 360 by sampling a given signal more than once per pole rotation. Further, the selection of sampling frequency (1) need not be made until after the digital data have been inspected, (2) can be varied during a given recording, and (3) may be made independently for each channel, with the restriction that the total number of samples/second cannot exceed 2160. Changing the projector-commutator synchronization ratio will allow a decrease or increase in the values just given. Other methods are also available for achieving higher sampling frequencies, but these methods will not be discussed since they would be seldom used in film research.

The continuous data at the input to the sampler are transformed by the sampler to pulse-amplitude data. These pulse-amplitude data from the six poles of the commutator are transferred to six tracks of a seven-track FM magnetic tape recorder (Precision Instruments, Model PS 207). Later, upon reproduction of the data at the computer facility, the data again appear in pulse-amplitude form. In effect, the recorder-reproducer is a vehicle which allows physiological activity in the classroom to be reproduced in the computing facility.

2. Computing Facility

At the computing facility the pulse-amplitude data are fed to an analog-to-digital converter (Packard Bell, Model M-3). The start-conversion pulse can be generated from the leading edge of the data pulse or from a timing track. Conversion to 11-bit straight binary is completed in 100 microseconds, at which time an end-of-conversion pulse is generated by the converter. This end-of-conversion pulse not only gates the 11 data pulses but also initiates execution of the data-input program. Data can be transferred to the computer at a tape speed different from that used in recording. Transfer is made to the SWAC computer by direct wire, and circuitry to allow this transfer has been designed and constructed as part of this project.

SWAC is a four-address machine with an elementary operation (add, for instance) of 64 microseconds.

Permanent records of the data are available in digital and analog form. Permanent digital records are available as punched card, digital tape, and printed listing. Punched cards are available in row-binary (10 values per card), column-binary (60 values per card), or decimal (10 values per card), digital tapes are available in binary or binary-coded decimal, and printed listings are available in tabular form. The generation of these records is performed by three computers: SWAC (which generates row-binary, column-binary, or decimal cards), an IBM 1401 (which generates binary tape or BCD tape), and an IBM 7090 (which generates binary tape or BCD tape). The 1401 is also used off-line to generate decimal cards or printed listing from the BCD tape generated by the 1401 or the 7090. Further, decimal cards generated by SWAC or the 1401 can be used to obtain printed listing from an accounting machine printer, such as the IBM 407.

Articulation between SWAC and the 1401 is by direct wire or cards, between SWAC and the 7090 by punched cards, and between the 1401 and the 7090 by punched cards or digital tape. Direct wire connection between the recorder-reproducer and SWAC, and between SWAC and the 1401 was a joint effort, with contributions made by the personnel of this study and of the UCLA Computing Facility.

As a result of this study considerable interest has been generated on campus in the use of digital machines in the analysis of analog phenomena. Until a year ago, at which time the system described in this report became operational, all digital analysis of analog phenomena required the preliminary analog-to-digital conversion to be undertaken by an operator. Today, only one year later, studies are being undertaken in many of the campus departments in the biological, physical, and behavioral sciences which may involve upwards of a million converted data values. Further, the data-handling developments which have resulted from this study are also receiving attention from other campuses, and research persons from as far away as

Fairbanks, Alaska have utilized these developments. Even more encouraging is the interest in extending the procedures utilized in this study. Similar facilities are now being installed in the Medical Center, and preliminary action has been started to allow analog-to-digital procedures to be used eventually with the two 7090's and the one 7094 at UCLA.

The effort expended in this project in obtaining the digital representation of an analog phenomenon is justified by the fact that the digital representation can contain all the information contained in the analog phenomenon, as will be shown in Part III. Nevertheless, analog representations make their own appeal to intuition, and it has been found useful to also retain analog representations of the phenomenon.

Permanent analog records are available as continuous magnetic records, discrete magnetic records, continuous graphic records, and discrete graphic records. Continuous magnetic records may be obtained if the number of channels is no greater than the number of tracks, while discrete magnetic records (up to 180 channels) are available by the procedure already discussed. Continuous graphic records are generally obtained before the signal is recorded on tape and after the signal is reproduced from tape, while discrete graphic records are generally obtained after the signal has been converted to digital. Continuous graphic records are generated from pen-writing or other direct-writing recorders, from oscillographic recorders, or from photographic recorders involving oscilloscope traces, while discrete graphic records are generated from discrete graphic plotters or from computers programmed to yield a printed listing which takes the form of points on a curve.

Data records, whether they exist temporarily in the computer or permanently outside the computer, have been discussed in this section on measurement rather than in the next section on analysis. This is as it should be, for in a broad sense, measurement is a procedure for describing the (analog or digital) representation of a phenomenon, whereas analysis is a procedure for manipulating this representation.

III. ANALYSIS OF PHYSIOLOGICAL RESPONSE TO FILM

About an equal amount of effort has been expended in the measurement and analysis aspects of this project. Again, it should be emphasized that the decision to present these two aspects as two different parts of this report was based on the assumption that greater clarity would result. Actually, measurement and analysis considerations were developed as a unit, and it could not be otherwise. For instance, sampling frequency and sampling duration are usually determined by the measurement procedure, but the values of these two parameters depend in large part on the type of analysis to be undertaken.

Part III of this report is divided into two sections similar to those of Part II. The first section below discusses the problems of analysis which were considered in this study. The second section describes the implementation of these considerations - the manner in which the data are analyzed currently.

A. ANALYSIS CONSIDERATIONS

Primary consideration was given to the relation between a continuous signal and its sampled representation. This consideration was necessitated by the fact that the phenomenon to be analyzed is continuous, whereas the measurement procedure results in the retention of sampled values of this continuous phenomenon.

Most physiological phenomena, such as skin resistance or EEG, are inherently continuous in time, and are usually represented as continuous signals. Other physiological phonomena, such as heart action, may be considered as discrete events, but even such phenomena are often represented as continuous signals. For the purposes of the following development no distinction need be made between these two types of continuous signals; a continuous signal is assumed, without regard to its source.

The main purpose of this section is to consider the sampled representation of a signal which was originally continuous in time. The

following paradigm will be assumed: a continuous signal is presented to a sampler, which samples the signal for a fixed duration at equal time intervals, resulting in a train of samples which constitutes the sampled signal. A description will be given first of some characteristics of the original continuous signal as it exists before sampling. Thereafter, it will be easier to describe this same signal after the sampling process.

1. Characteristics of the Pre-Sampled Signal

The pre-sampled continuous signal may be represented in either the time domain or in the frequency domain. These representations carry the same information and are mathematically equivalent. However, each representation makes a different appeal to intuition, and for this reason, as well as for heuristic value, both representations will be employed. Throughout this section, the pre-sampled continuous signal will be designated by f(t) when the signal is represented in the time domain, and by $F(\omega)$ when the same signal is represented in the frequency domain.

Inasmuch as both representations are equivalent, either representation may be transformed into the other. Transformation of the time representation to the frequency representation is by way of the direct Fourier transform of f(t), which yields the frequency function $F(\omega)$.

$$F(\omega) = \int_{-\infty}^{\infty} f(t)\, e^{-j\omega t} dt \qquad (1)$$

The inverse Fourier transform of $F(\omega)$ allows f(t) to be expressed in terms of the frequency function $F(\omega)$.

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega)\, e^{j\omega t}\, d\omega \qquad (2)$$

Equations (1) and (2) form the Fourier transform pair of f(t).

Part IV of this report presents an experimental study involving the classroom measurement of the skin resistance response, which is related to the galvanic skin response. Here we are concerned only with the characteristics of this phenomenon. Equations (1) and (2) have been presented

because they will form the basis for the following discussion of these characteristics, as well as the basis for much of the material to be presented throughout Part III.

If a stimulus is applied at time $t = 0$, then a drop in skin resistance is detectable a short time later. It reaches a minimum soon thereafter, then returns slowly to its original basal value. This phenomenon, beginning at $t = 0$ and extending to infinity, will be referred to as the skin resistance response.

Traditionally, the skin resistance response is measured only at a particular point in time. For instance, its measurement often involves values of the basal skin resistance and of the decrease in skin resistance at a particular point in time, usually at the instant at which the skin resistance is minimal. These two values are often combined into a single measure, often involving logarithmic or exponential transformations.

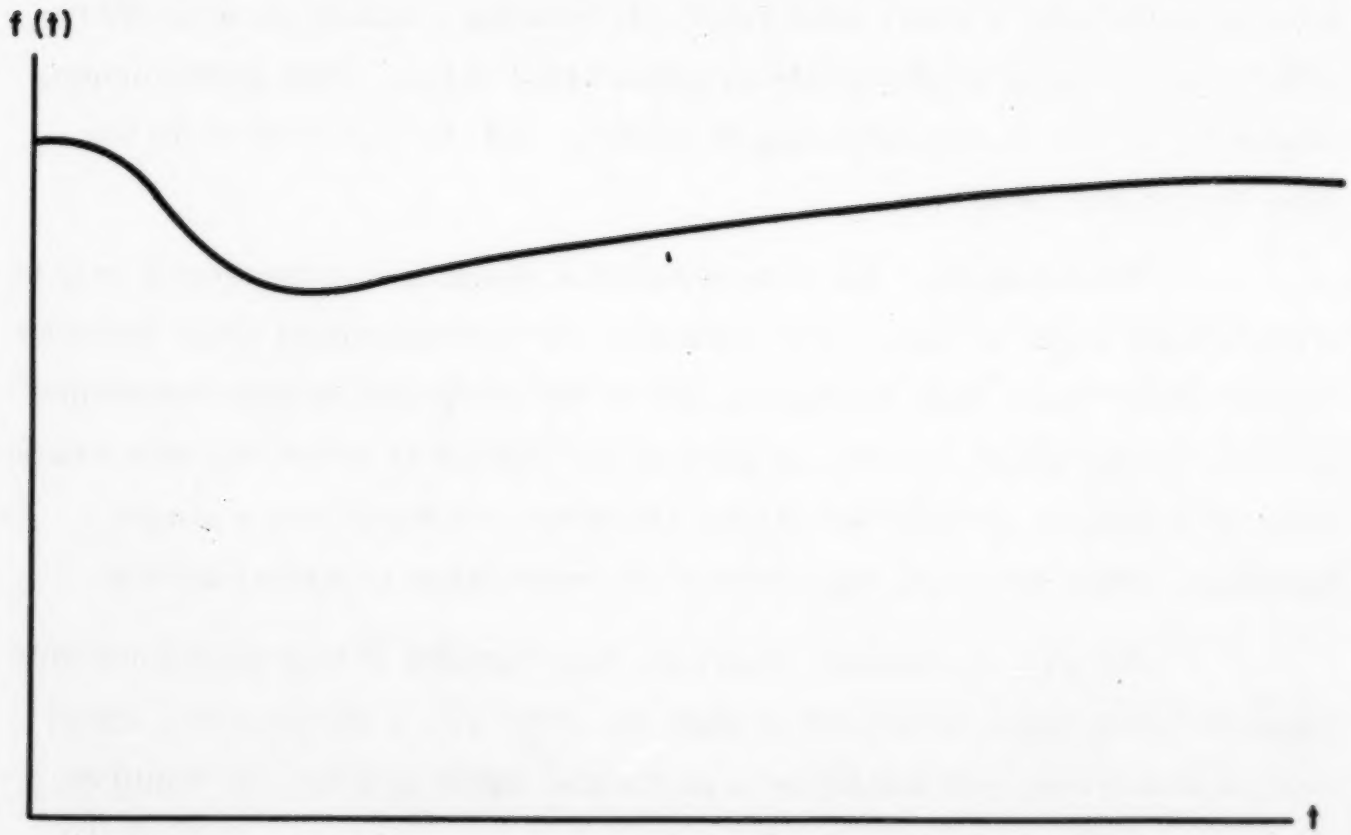
All skin resistance response descriptions of this type constitute impoverished representations of what is, after all, a phenomenon which occurs over time, not simply at a particular point in time. It would be more appropriate to represent the skin resistance response without the loss of information characteristic of conventional descriptions.

The continuous skin resistance response may be represented in either the time or frequency domain. Since most people find it more natural to conceive of the skin resistance response as a phenomenon in time, the phenomenon will be represented first in the time domain.

The skin resistance response may be represented by the function

$$f(t) = \begin{cases} r_o(1 - kt^n e^{-at}) & t \geq 0 \\ r_o & t < 0 \end{cases} \qquad (3)$$

where r_o is the basal skin resistance, and k, a, and n are parameters, with the value of n restricted to positive integers greater than 1. Equation (3) is plotted in Figure 3 for typical values of k, a, and n.



PRE-SAMPLED SKIN RESISTANCE RESPONSE IN THE TIME DOMAIN
FIGURE 3

In order to express the skin resistance response in the frequency domain, Equation (1) is applied to Equation (3). In applying this transform to the skin resistance function, it is convenient to break up the integral according to the limits suggested by Equations (3).

$$F(\omega) = \int_{-\infty}^{0-} r_o e^{-j\omega t}\, dt + \int_{0}^{\infty} r_o (1 - kt^n e^{-at}) e^{-j\omega t}\, dt$$

$$= r_o \left[\int_{-\infty}^{\infty} e^{-j\omega t}\, dt - k \int_{0}^{\infty} t^n e^{-at} e^{-j\omega t}\, dt \right] \qquad (4)$$

The first integral is the transform of unity, that is, the transform of a function which is unity for all time. This transform may be evaluated by employing Equation (2), the inverse transform of $F(\omega)$.

The first integral in Equation (4) will have been evaluated when a function $F(\omega)$ is specified such that its introduction into Equation (2) yields unity. The function $F(\omega)$ for which we seek is most readily found by the use of the unit impulse function.

The unit impulse function (or delta function) is defined by the relations

$$\delta(x-b) = \begin{cases} \infty & x = b \\ 0 & \text{otherwise} \end{cases}$$

$$\int_{-\infty}^{\infty} \delta(x-b)dx = \int_{b^-}^{b^+} \delta(x-b)dx = 1$$

That is, the unit impulse function is zero for all x except at b, where it is infinite in such a manner that integration over b yields unity. It may be thought of as the limit of a pulse of unit height and unit width, which becomes increasingly higher and narrower in such a fashion as to retain unit area.

The delta function can also be considered as the limit of several other functions, such as the Gaussian probability density function. This function is defined by the relations

$$p(x) = \frac{1}{\sigma\sqrt{2\pi}} \; e^{-\frac{1}{2}\left(\frac{x}{\sigma}\right)^2}$$

and

$$\int_{-\infty}^{\infty} p(x)\, dx = 1$$

In the limit, as $\sigma \to 0$, p(x) becomes the impulse function.

Let $\delta(\omega - 0)$ be introduced as $F(\omega)$ in Equation (2).

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \delta(\omega - 0)\, e^{j\omega t}\, d\omega$$

This f(t) becomes $\frac{1}{2\pi}$, a direct result of the definition of the delta function as zero for all frequencies except $\omega = 0$, at which point $e^{j\omega t}$ becomes unity, resulting in an integral whose value is 1.

It should be noted that $e^{j\omega t}$ is continuous at the origin, for as Dirac (1935) points out, the delta function has meaning only when used as part of an integrand with another function which is continuous at the point where the impulse is located - in this case at $\omega = 0$ (Aseltine, 1958).

Since $\delta(\omega - 0)$ in the equation above yields an f(t) of $\frac{1}{2\pi}$, we know that $2\pi\ \delta(\omega - 0)$ would yield an f(t) of unity. Therefore, $2\pi\ \delta(\omega - 0)$ is the frequency function for which we have been searching. Thus, the first integral of Equation (4) has been evaluated.

$$\int_{-\infty}^{\infty} e^{-j\omega t}\, dt = 2\pi\ \delta(\omega - 0)$$

The second integral of Equation (4) can be considered a Laplace transform, inasmuch as the lower limit of integration is zero (Savant, 1962). One advantage of considering it as a Laplace, rather than a Fourier, transform derives from the fact that the Laplace transform has been tabled more extensively. From such a table (Aseltine, 1958),

$$\int_{0}^{\infty} t^n\, e^{-at}\, e^{-j\omega t}\, dt = \frac{n!}{(a + j\omega)^{n+1}}$$

Combining both integrals,

$$F(\omega) = r_o\left[2\pi\,\delta(\omega-0) - \frac{k\,n!}{(a+j\omega)^{n+1}}\right]$$

The last term is multiplied by the conjugate of the denominator in order to remove the imaginary from the denominator.

$$F(\omega) = r_o\left[2\pi\,\delta(\omega-0) - \frac{k\,n!(a-j\omega)^{n+1}}{(a^2+\omega^2)^{n+1}}\right]$$

By expressing the numerator as a binomial expansion,

$$F(\omega) = r_o\left[2\pi\,\delta(\omega-0) - \frac{k\,n!}{(a^2+\omega^2)^{n+1}}\sum_{r=0}^{n+1}\frac{(n+1)!}{(n+1-r)!\,r!}\,a^{n+1-r}(-j\omega)^r\right]$$

In general, as in this case, the transform is complex. Whereas f(t) is a real function of time, $F(\omega)$ is generally a complex function of frequency. $F(\omega)$ may also be written as an amplitude and a phase angle, both functions of ω. Often, the phase angle is of little interest and is not specified.

In order to evaluate the amplitude of the expression given above, the real terms of the binomial expansion should be separated from the imaginary terms. When this procedure is carried out with the parameter values used to plot Figure 3 ($k = .01$, $a = .2$, $n = 2$),

$$F(\omega) = r_o\left\{\left[2\pi\,\delta(\omega-0) + \frac{.012\,\omega^2 - .00016}{(.04+\omega^2)^3}\right] + j\left[\frac{.0024\,\omega - .02\,\omega^3}{(.04+\omega^2)^3}\right]\right\}$$

The amplitude of $F(\omega)$, designated by $|F(\omega)|$, is the positive square root of the sum of the squares of the real and imaginary parts, and its plot is referred to as a frequency spectrum.

$$|F(\omega)| = r_o\left\{\left[2\pi\,\delta(\omega-0) + \frac{.012\,\omega^2 - .00016}{(.04+\omega^2)^3}\right]^2 + \left[\frac{.0024\,\omega - .02\omega^3}{(.04+\omega^2)^3}\right]^2\right\}^{1/2}$$

This function is plotted in Figure 4.

The square of the real part in the equation above contains two terms. The first is infinite at the origin and zero elsewhere, allowing one to ignore the $2\pi\,\delta(\omega-0)$ term except at $\omega = 0$. The $2\pi\,\delta(\omega-0)$ term has not been plotted at the origin, but if it had it would have been represented by an arrow. If Figure 4 were represented as a histogram, the delta term would contribute to the height of the bar straddling the origin a value equal to 2π divided by the width of the bar. The second term in the real part in the equation above, would contribute to this same bar an amount equal to its integral over the bar.

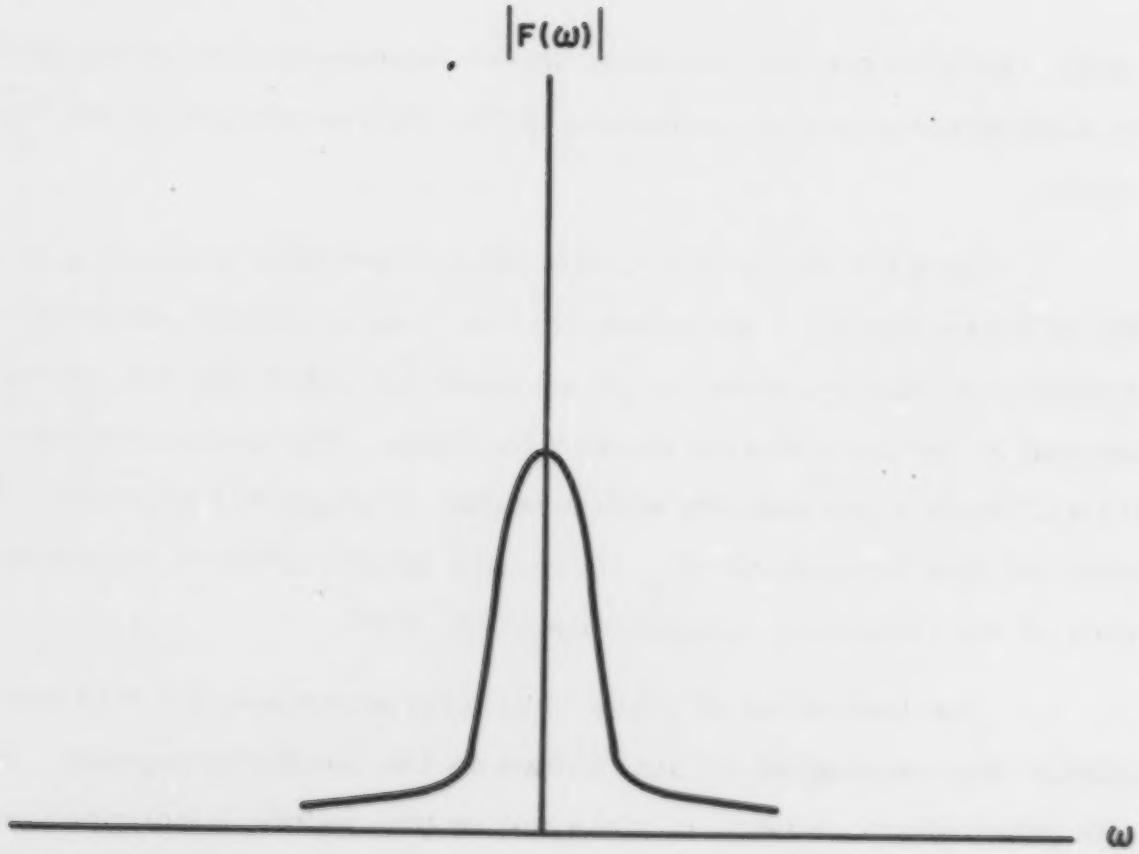
The graphic representations in the time and frequency domains of skin resistance responses obtained in the classroom as part of this project, were similar to the analytically derived representations shown in Figures 3 and 4.

Another phenomenon which is likely to become important in educational research is the EEG. Its measurement in the classroom during normal learning situations imposes technological problems which will have to be overcome first. In anticipation of its future importance in research in the areas of learning, thinking, and perception, a brief discussion will be given of the objective analysis of EEG. This second example is intended also to indicate that Equations (1) and (2) are useful in analyses in which functions are known only implicitly.

A commonly used function in the analysis of brain waves is the autocorrelation function,

$$f(\tau) = \lim_{T_o \to \infty} \frac{1}{2T_o} \int_{-T_o}^{T_o} g(t)g(t+\tau)\,dt$$

where τ is a time lag.



PRE-SAMPLED SKIN RESISTANCE RESPONSE IN THE FREQUENCY DOMAIN
FIGURE 4

The direct Fourier transform of the autocorrelation function is known as the spectral density function. When $f(\tau)$ is put into Equation (1),

$$F(\omega) = \int_{-\infty}^{\infty} f(\tau)\, e^{-j\omega\tau}\, d\tau$$

The inverse Fourier transform of $F(\omega)$ is obtained from Equation (2) as

$$f(\tau) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega)\, e^{j\omega\tau}\, d\omega$$

Again, the information contained in the representation of the phenomenon in the time domain is also contained in the representation in the frequency domain.

In EEG analysis the detection of periodic signals is of interest. One of these signals - the alpha rhythm - is located at about 10 cps. The existence of this phenomenon is revealed by either the autocorrelation function or by the spectral density function. The autocorrelation function $f(\tau)$ will show a periodicity with a period of about 0.1 seconds. The attenuation of this function as T_o increases is indicative of variation in one or more of the frequency components in the EEG.

An indication of these characteristics may be obtained by a graphic representation of $f(\tau)$ known as the autocorrelogram. A single autocorrelogram, however, does not reveal as much information as is contained in the EEG signal, for it treats T_o as a parameter, rather than as a variable. Strictly speaking, of course, the autocorrelation function is defined only in the limit as $T_o \to \infty$, but in practice useful information may be revealed by considering T_o as a variable.

The alpha rhythm revealed by the autocorrelation function is also revealed by the spectral density function, and, in fact, the amplitude of this latter function probably has a greater intuitive appeal for most people. A plot of the amplitude of the spectral density function will show a peak near 10 cps, and the magnitude and variance of this peak with respect to the rest of the frequency spectrum contain information of interest.

Analogous to the autocorrelation function is the cross-correlation function, which is used to advantage when the relation between two EEG signals is of interest. Consider two EEG signals recorded simultaneously from two points on the scalp. One relation between these two signals, a relation which utilizes time as a basis, is given by the cross-correlation function

$$f(\tau) = \lim_{T_o \to \infty} \frac{1}{2T_o} \int_{-T_o}^{T_o} g(t)h(t+\tau)\, dt$$

where the second time function $h(t+\tau)$ has been delayed a time τ. Of greatest interest is likely to be that value of τ for which $f(\tau)$ is maximum.

The cross-correlation function is a time function and may be Fourier transformed by Equation (1). The resulting frequency function,

$$F(\omega) = \int_{-\infty}^{\infty} f(\tau)\, e^{-j\omega\tau}\, d\tau$$

is known as the cross-spectral density function. In general, $F(\omega)$ will be a complex function, but interest may be restricted to the amplitude or to the phase angle between the real and imaginary parts. The phase angle will be a function of frequency, and, in conjunction with τ, may reveal significant information.

These two examples have shown the application of the Fourier transform pair - Equations (1) and (2) - two functions which are likely to be useful in educational research. The first example involved explicit functions, whereas the second involved implicit functions. Frequently, explicit functions will not be known for the signal under investigation, but this need not prevent the display of the signal in the time or frequency domain. The relations specified by Equations (1) and (2) hold for any signal for which a function is possible, even though the function may not be known explicitly.

The consideration so far has involved a continuous psychophysiological signal before it has been sampled. The discussion will turn now to the characteristics of this same signal after it has been sampled.

2. Characteristics of the Sampled Signal

In the previous section, the pre-sampled signal was designated by $f(t)$ in the time domain, and by $F(\omega)$ in the frequency domain. In this section, the same signal will be designated by $f^*(t)$ and $F^*(\omega)$ after it has been sampled. The effect of sampling is known when $f^*(t)$ is described in terms of $f(t)$, and $F^*(\omega)$ in terms of $F(\omega)$.

Assume that the signal $f(t)$ is sampled at equal intervals. Let ω_s denote the sampling frequency (the number of samples per unit time), T the sampling period (the time between samples), and d the sampling duration (the time duration for which the sampling switch is closed). In general, d is very much less than T.

The output of such a sampler is a signal which is zero except when the switch is closed. During the time the switch is closed, the output signal is proportional to the input signal $f(t)$. Thus, the output signal $f^*(t)$ consists of a train of values.

The characteristics of the sampled signal are most readily described in mathematical terms, and such a description requires an expression for $f^*(t)$. Such an expression may be obtained by considering the sampler as a modulator (Tou, 1959). In this context, the sampling process may be conceived of as a modulation process whereby a signal function $f(t)$ modulates a carrier function $p(t)$. This conception, which will be utilized throughout this report, allows $f^*(t)$ to be expressed as a multiplicative function of $f(t)$ and $p(t)$. Thus,

$$f^*(t) = f(t)\ p(t) \tag{5}$$

Inasmuch as the sampling period T is constant, $p(t)$ is a periodic function, and may be expanded in a Fourier series in t, with the Fourier coefficient associated with the nth harmonic given by

$$c_n = \frac{1}{T} \int_{-T/2}^{T/2} p(t)\, e^{-jn\omega_s t}\, dt \tag{6}$$

where ω_s is the sampling frequency (equivalent to a fundamental frequency). Then

$$p(t) = \sum_{n=-\infty}^{\infty} c_n e^{jn\omega_s t} \tag{7}$$

Substituting Equation (7) in Equation (5),

$$f^*(t) = \sum_{n=-\infty}^{\infty} c_n f(t) e^{jn\omega_s t} \tag{8}$$

Equation (8) is the basic expression for the sampled signal in the time domain. The basic frequency domain expression $F^*(\omega)$ for the same signal may be obtained from Equation (8) by application of the shifting theorem (Ragazzini and Franklin, 1958). This theorem states that

$$\mathcal{F}\left[f(t)\, e^{\lambda t} \right] = F(j\omega - \lambda) \tag{9}$$

where $\mathcal{F}$ denotes the Fourier transform operator, and $F(\omega)$ is the Fourier transform of $f(t)$. Applying the operation described by Equation (9) to both sides of Equation (8),

$$F^*(\omega) = \sum_{n=-\infty}^{\infty} c_n F(\omega - n\omega_s) \tag{10}$$

where the complex characteristic of this and other frequency functions is implied.

Before developing Equations (8) and (10) more fully, it is instructive to note the relationship between the pair of Equations (6) and (7) and the pair of Equations (1) and (2). Equation (6) is the direct finite Fourier transform of $p(t)$, while Equation (7) is the inverse finite Fourier transform of c_n. These equations constitute a special case of the more general Fourier transform equations. In fact, any periodic function may be changed into the more general nonperiodic function by letting the period become large without bound. Thus, it is possible to generalize Equation (6)

so as to obtain Equation (1), as well as to generalize Equation (7) so as to obtain Equation (2). To do this we note that an increment in ω_s (the fundamental frequency, in this case the sampling frequency) is given by

$$\Delta(n\omega_s) = (n+1)\omega_s - n\omega_s = \frac{2(n+1)\pi}{T} - \frac{2n\pi}{T} = \frac{2\pi}{T} \tag{11}$$

After substituting Equation (11) into Equation (7), Equations (6) and (7) become

$$c_n = \frac{1}{T} \int_{-T/2}^{T/2} p(t)\, e^{-jn\omega_s t}\, dt$$

$$p(t) = \frac{T}{2\pi} \sum_{n=-\infty}^{\infty} c_n\, e^{jn\omega_s t}\, \Delta(n\omega_s)$$

If we let $T\, c_n = F(n)$,

$$F(n) = \int_{-T/2}^{T/2} p(t)\, e^{-jn\omega_s t}\, dt$$

$$p(t) = \frac{1}{2\pi} \sum_{n=-\infty}^{\infty} F(n)\, e^{jn\omega_s t}\, \Delta(n\omega_s)$$

Now if we let $T \to \infty$ in such a way that $(n\omega_s)$ approaches a continuous variable ω, the sum becomes formally an integral, and $p(t)$ is no longer restricted to a carrier function and may be written as $f(t)$. Then,

$$F(\omega) = \int_{-\infty}^{\infty} f(t)\, e^{-j\omega t}\, dt$$

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega)\, e^{j\omega t}\, d\omega$$

The two equations above constitute the Fourier transform pair given as Equations (1) and (2). These two equations, together with Euler's equation,

$$e^{\pm j\omega t} = \cos \omega t \pm j \sin \omega t \qquad (12)$$

allow any function to be represented in terms of sines and cosines. If the function is periodic, then only discrete frequencies are present, and f(t) is given by the sum of the sinusoids of these discrete frequencies. If the function is not periodic, then all frequencies are present, and f(t) is given by the integral of the sinusoids of all frequencies.

Having indicated that Equations (6) and (7) constitute the Fourier transform pair for the special case of periodic signals, we now return to the development of Equations (8) and (10).

The Fourier coefficients - the c_n's - in Equation (8) are described in terms of the carrier function p(t), as is indicated by Equation (6). Hence, before f*(t) can be described more fully, it will be necessary to obtain an expression for p(t).

The sampling function p(t) may be conceived of as representing a hypothetical train of pulses separated by time T, with each pulse having a width equal to the sampling duration d. As will become apparent, it is desirable to have d as small as possible. The ideal case is to have d infinitesimally small, and for such a case, p(t) is referred to as the ideal sampling function. This ideal case is never achieved in practice, since d must be finite for any real sampler. Nevertheless, it is instructive to describe the sampling process in terms of an infinitesimal sampling duration before describing the sampling process in terms of a finite sampling duration. Through such an approach, the effect of sampling duration will become more readily apparent.

Two sampling functions will be employed: one for the case of an infinitesimal sampling duration, the other for the case of a finite sampling duration. For the initial discussion involving an infinitesimal sampling duration, the sampling function p(t) will be based on a train of impulses, each of which is infinite in such a fashion that integration over the impulse

yields unit area; this sampling function will be referred to as the impulse sampling function. Thereafter, during the subsequent discussion involving a finite sampling duration, the sampling function p(t) will represent a train of pulses, each of which has a width of d and a height of unity; this sampling function will be referred to as the pulse sampling function.

Infinitesimal Sampling Duration. For the idealized sampler, the signal f(t) is passed at instants $t = 0, T, 2T, \ldots, kT$. At these instants the output of the sampler has the values $f(0), f(T), f(2T), \ldots, f(kT)$, and at all other times the output is zero. Figure 5 shows in the time domain the previously discussed skin resistance response after it has been sampled. The pre-sampled signal is shown by a dashed curve.

It is recalled that the sampling process is conceived of as a modulation process. The development of Equations (8) and (10) was based on this conception. These two equations require an expression for c_n, which is obtained from Equation (6) for a particular sampling function p(t).

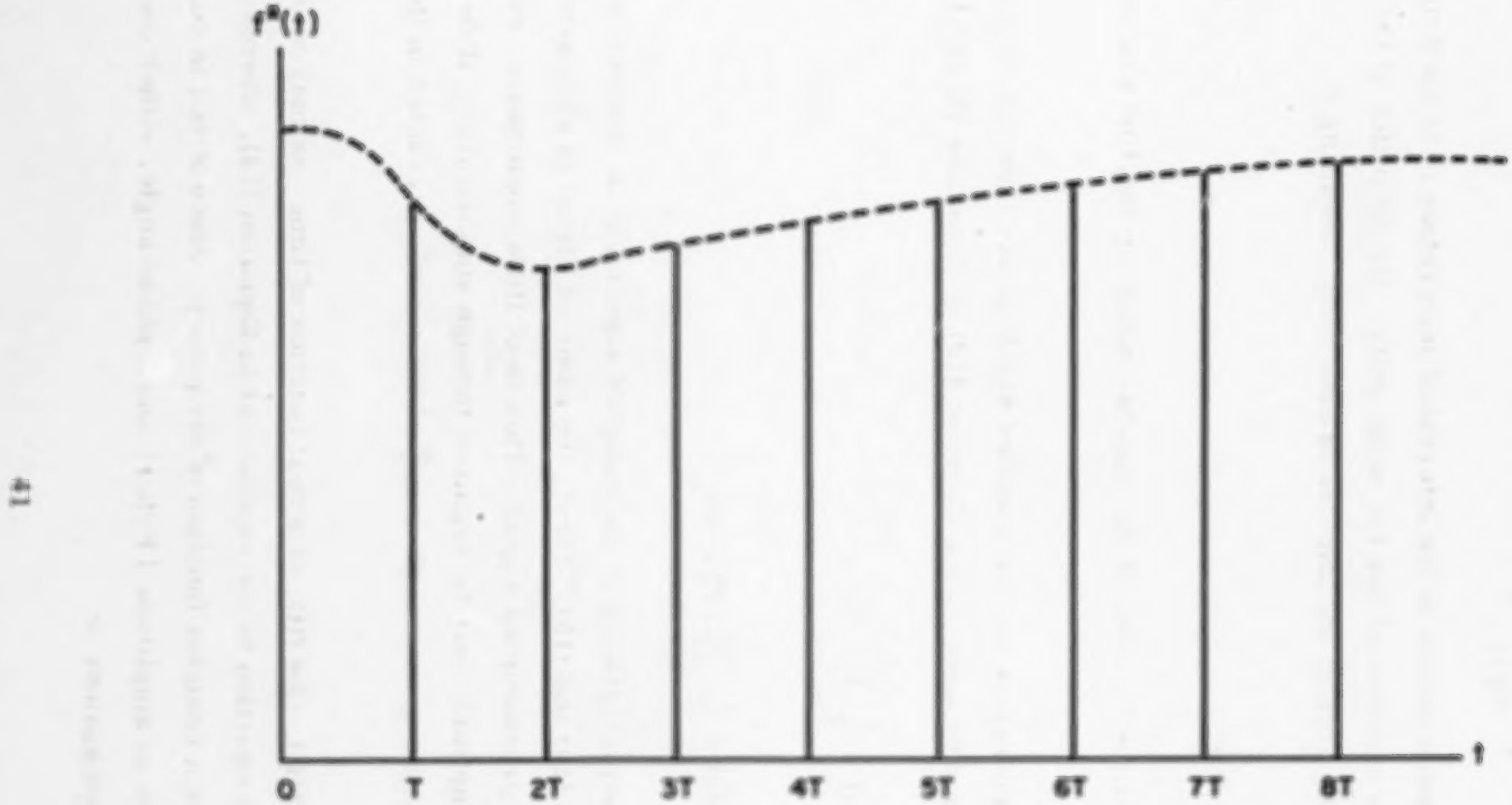
The sampling function employed in this section is based on the unit impulse function $\delta(t-kT)$, previously introduced as a frequency function during the discussion of the pre-sampled signal. In the time domain, the unit impulse function (delta function) is defined by the relations

$$\delta(t - kT) = \begin{cases} \infty & t = kT \\ 0 & \text{otherwise} \end{cases}$$

$$\int_{-\infty}^{\infty} \delta(t-kT)\, dt = 1$$

It is seen that the unit impulse function located at any instant kT is infinite in such a manner that integration over that instant yields unity. The impulse sampling function $\delta_T(t)$ is defined as

$$\delta_T(t) \triangleq \sum_{k=-\infty}^{\infty} \delta(t-kT)$$



SAMPLED SKIN RESISTANCE RESPONSE IN THE TIME DOMAIN
(Infinitesimal Sampling Duration)

FIGURE 5

When $\delta_T(t)$ is substituted for $p(t)$ in Equation (6),

$$c_n = \frac{1}{T} \int_{-T/2}^{T/2} \delta_T(t)\, e^{-jn\omega_s t}\, dt$$

The only impulse which occurs in the interval of integration is at the origin, and at this point the exponential has the value unity. By definition of the unit impulse function, the area of the impulse is also unity, resulting in

$$c_n = \frac{1}{T} \tag{13}$$

That is, the Fourier coefficients of the impulse sampling function are independent of n.

Now, expressions for the sampled signal in the time and frequency domains are obtained by substituting Equation (13) in Equations (8) and (10).

$$f^*(t) = \frac{1}{T} \sum_{n=-\infty}^{\infty} f(t)\, e^{jn\omega_s t} \tag{14}$$

$$F^*(\omega) = \frac{1}{T} \sum_{n=-\infty}^{\infty} F(\omega - n\omega_s) \tag{15}$$

Three characteristics of the sampled signal will be discussed in terms of Equations (14) and (15). First, the sampled signal is attenuated with respect to the pre-sampled signal. This is of little importance, since the pre-sampled amplitude may be regained through amplification, if desired. The attenuation is not shown in any of the figures presented in this report.

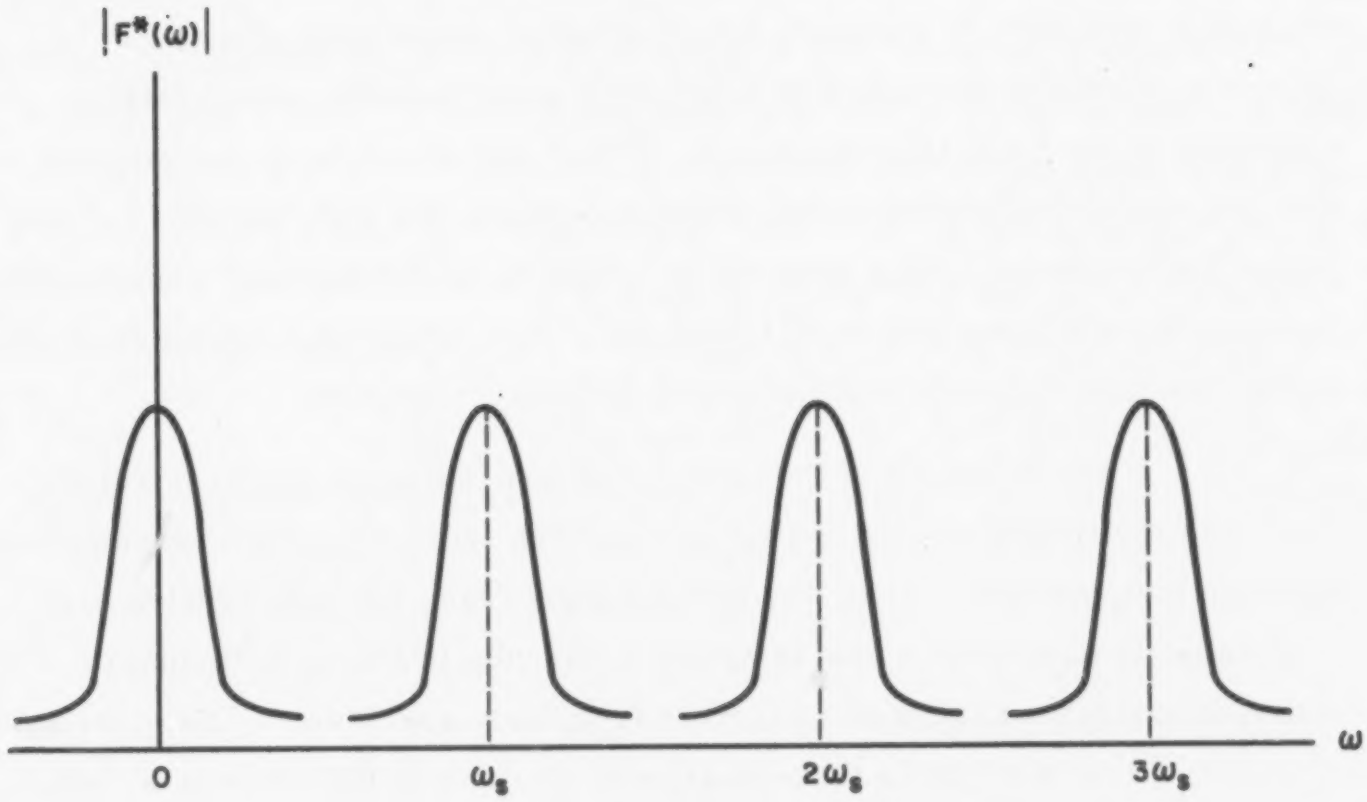
Second, $f^*(t)$, like $f(t)$, is a real function of time, as may be seen by applying Euler's equation to the exponential in Equation (14), whereas $F^*(\omega)$, like $F(\omega)$, is a complex function of frequency. Since $F^*(\omega)$ is complex, it may be written as an amplitude $|F^*(\omega)|$ and a phase angle, either one of which may be plotted against ω.

Third, $F^*(\omega)$ contains not only a primary component located at the origin but also an infinite number of complementary components located at multiples of the sampling frequency. Figure 6, a plot of $|F^*(\omega)|$ for the same skin resistance response used for Figures 3-5, shows the primary component and three of these complementary components in the positive frequency domain. A complete representation would show that the component centered on the origin is replicated at all positive and negative multiples of the sampling frequency. These complementary components are the result of a mixing of the original frequencies with multiples of the sampling frequency. This periodicity property of the sampled signal exists because the sampling process is periodic. The sampling process generates a discrete time function and a periodic frequency function.

It should be noted that a periodic pre-sampled signal is represented in the frequency domain by line spectra (vertical lines representing specific frequencies). After the sampling process, the line spectra are replicated at multiples of the sampling frequency in the usual manner. Thus, a periodic signal possesses a discrete frequency spectrum. The emergence of line spectra is of aid in those analyses, such as in EEG analysis, where the detection of periodicity is of interest.

Of the infinity of components in the frequency spectrum, the primary component is the desired signal. This signal can be recovered by filtering the unwanted complementary components as long as the sampling frequency is at least twice the highest component in the pre-sampled signal. If the sampling frequency is not twice the highest component in the pre-sampled signal, then portions of the complementary components will overlap the primary component, as may be visualized in Figure 6. This overlap results in a sampled signal which is different from the pre-sampled signal. The sampled signal is inflated in the frequency region of overlap.

The lowest permissible sampling frequency is limited by the maximum error due to overlap which can be tolerated in the frequency representation of the signal. This maximum error usually occurs at the



SAMPLED SKIN RESISTANCE RESPONSE IN THE FREQUENCY DOMAIN
(Infinitesimal Sampling Duration)

FIGURE 6

maximum frequency of interest, ω_m. A common technique for reducing this overlap error is to attenuate the signal for frequencies above ω_m before the signal is presented to the sampler. For instance, assume that the overlap error is to be restricted to 1% at ω_m. Assume further that the sampler is preceded by a low-pass filter with an attenuation factor of -20db per octave for frequencies above ω_m, so that at $4\omega_m$ the amplitude of $F(\omega)$ is -40db (1%) of its value at ω_m. After sampling, the frequency spectrum folded about ω_s will overlap the frequency spectrum centered on the origin by only 1% as long as ω_s is five times the maximum frequency of interest.

This example reveals that the sharper the cutoff of $F(\omega)$ above ω_m, the lower the permissible sampling frequency. In the ideal case of a vertical cutoff at ω_m, the sampling frequency need be only $2\omega_m$, provided that the replicated spectra introduced by sampling are filtered by vertical cutoff at ω_m before analysis proceeds. In practice, however, extremely sharp cutoff filtering is not obtained, either before sampling or before analysis, forcing practical sampling frequencies of 5 to 10 times ω_m.

It is important to note that if the sampling process introduces frequency components in the range $(0 - \omega_m)$, thereafter these components cannot be filtered out electrically or numerically. Hence, if an undesired frequency - say 60 cps interference - exists in the signal presented to the sampler, it would be desirable to have a sampling frequency such that the frequencies $(n\omega_s \pm 2\pi 60)$, where n is any integer, do not fall in the region $(0 - \omega_m)$.

However, if the sampling frequency is at least twice the highest frequency component in the pre-sampled signal, the sampled signal contains the same information contained in the pre-sampled signal. This fundamental theorem was developed by Shannon and is known as the sampling theorem (Oliver, Pierce, and Shannon, 1948).

To prove the sampling theorem, assume a signal whose highest frequency component is ω_h, and let such a signal be sampled at a sampling frequency

$$\omega_s = 2\omega_h \tag{16}$$

After sampling, the signal will be represented in the frequency domain by the pre-sampled frequency spectrum located at the origin, as well as by replications centered at multiples of the sampling frequency. Thus, the frequency spectrum is periodic, and may therefore be represented by a Fourier series in ω. The complementary signals (sidebands) are of no consequence, since the Fourier series is defined only in the range $-\omega_h \leq \omega \leq \omega_h$. This periodic spectrum, with a fundamental frequency of $2\omega_h$, may be represented by

$$F(\omega) = \sum_{k=-\infty}^{\infty} c_k \, e^{-j\omega kT} \tag{17}$$

where T is the sampling period, and the c_k's are the Fourier coefficients defined by

$$c_k = \frac{1}{2\omega_h} \int_{-\omega_h}^{\omega_h} F(\omega) \, e^{j\omega kT} \, d\omega \tag{18}$$

If the values of the Fourier coefficients can be determined, then the frequency spectral function $F(\omega)$ can be obtained from Equation (17). And when the Fourier transform of a signal $f(t)$ is specified, the signal itself is fully specified.

In order to develop an expression which allows the values of c_k to be determined, use is made of the inverse transform relationship given in Equation (2).

$$f(t) = \frac{1}{2\pi} \int_{-\omega_h}^{\omega_h} F(\omega) \, e^{j\omega t} \, d\omega \tag{19}$$

where the limits are justified by the fact that the Fourier spectrum is band-limited at $-\omega_h$ and ω_h radians/second. At sampling instants $t = kT$, Equation (19) becomes

$$f(kT) = \frac{1}{2\pi} \int_{-\omega_h}^{\omega_h} F(\omega)\, e^{j\omega kT}\, d\omega \qquad (20)$$

It is seen that the integral in Equation (18) is equal to the integral in Equation (20). By combining these two equations,

$$c_k = T\ f(kT) \qquad (21)$$

Thus, the Fourier coefficients can be specified in terms of the values of the signal at the sampling instants as long as the condition expressed by Equation (16) is met - that is, as long as the sampling frequency is twice the highest frequency component in the pre-sampled signal. If the sampling frequency were not at least this high, then the limits of integration in Equation (18) would have been less than those in Equation (20), and these two equations could not have been combined to produce the result given in Equation (21).

The converse of the sampling theorem implies that the signal may be reconstructed completely from its sampled values as long as these sampled values are obtained at a sampling frequency which is at least twice the highest frequency component in the signal.

The reconstruction of the pre-sampled signal from its samples may be demonstrated by expressing $f(t)$ as the inverse transform of $F(\omega)$ for that case in which the sampling frequency ω_s is twice the highest frequency component in the signal. This is accomplished by first expressing $F(\omega)$ in terms of the signal at the sampling instants.

From Equation (2), the value of the signal at the kth sampling instant is given by

$$f(kT) = \frac{1}{2\pi} \int_{-\omega_h}^{\omega_h} F(\omega)\, e^{j\omega kT}\, d\omega \tag{22}$$

where T is the sampling period. Under the condition imposed by Equation (16), substitution of Equation (21) in Equation (17) yields

$$F(\omega) = T \sum_{k=-\infty}^{\infty} f(kT)\, e^{-j\omega kT} \tag{23}$$

Substituting Equation (23) into Equation (2) leads to

$$f(t) = \frac{T}{2\pi} \int_{-\omega_h}^{\omega_h} \sum_{k=-\infty}^{\infty} f(kT)\, e^{-j\omega kT}\, e^{j\omega t}\, d\omega$$

Interchanging the operation of summation and integration,

$$f(t) = \frac{T}{2\pi} \sum_{k=-\infty}^{\infty} f(kT) \int_{-\omega_h}^{\omega_h} e^{j\omega(t-kT)}\, d\omega$$

$$= \frac{T}{2\pi} \sum_{k=-\infty}^{\infty} f(kT)\, \frac{e^{j\omega(t-kT)}}{j(t-kT)} \Bigg|_{-\omega_h}^{\omega_h}$$

$$= \frac{T}{2\pi} \sum_{k=-\infty}^{\infty} f(kT)\, \frac{e^{j\omega_h(t-kT)} - e^{-j\omega_h(t-kT)}}{j(t-kT)}$$

$$= \frac{T}{\pi} \sum_{k=-\infty}^{\infty} f(kT)\, \frac{\sin \omega_h (t-kT)}{(t-kT)}$$

Since $\omega_h = \frac{\pi}{T}$,

$$f(t) = \sum_{k=-\infty}^{\infty} f(kT)\, \frac{\sin \omega_h(t-kT)}{\omega_h(t-kT)} \tag{24}$$

Equation (24) is an expression for the pre-sampled signal in terms of its sampled values and a function of time. The function

$$\frac{\sin \omega_h(t-kT)}{\omega_h(t-kT)} \tag{25}$$

equals unity when t equals kT (as may be seen by applying Lhopital's theorem), and vanishes whenever t attains any other integral value of T- that is, at any other sampling instant. Thus, for a given value of k, the function given in Equation (25) is a damped sinusoid folded about an ordinate at kT. The reconstructed curve at any point in time is the summation at that point of an infinite number of these damped sinusoids, one for each value of k.

This subsection has described the original pre-sampled psychophysiological signal after it has been sampled. It was assumed that the sampling frequency (sampling rate) was constant, and that the sampling duration (the time during which the signal is sampled) was infinitesimal. Although this last assumption is unrealistic, it allowed a relatively simple description of the sampled signal. In the next subsection a more realistic sampler will be assumed - one with a finite sampling duration.

Finite Sampling Duration. In the last subsection, it was convenient to conceive of the sampler as a modulator with the impulse sampling function modulated by the pre-sampled signal f(t). In this subsection the sampler will again be considered as a modulator with the pulse sampling function modulated by f(t).

The basic aspects of the sampler assumed in this subsection are similar to the sampler of the last subsection: the sampler is still a constant-rate device with sampling frequency ω_s and sampling period T, where $\omega_s = \frac{2\pi}{T}$. But whereas the sampler in the previous subsection was conceived of as a modulator with a carrier signal consisting of a train of impulses, the sampler in this subsection is conceived of as a modulator with a carrier signal consisting of a train of pulses, each of width d and height unity. It is assumed that d is very much less than T.

When the pulse sampling function, consisting of a train of pulses, each pulse of width d and height unity, is modulated by f(t), the result is a train of pulses of width d and height equal to f(t) during the occurrence of the pulses. Thus, the sampler is a device which acts as a pulse amplitude

modulator. A graphic representation in the positive time domain is given in Figure 7 for the output of the sampler when the same skin resistance response shown in Figure 3 is presented to the sampler.

The pulse sampling function is based on the unit pulse function, which is defined by the relations

$$u(t) = \begin{cases} 1 & kT \leq t \leq (kT + d) \\ 0 & \text{otherwise} \end{cases}$$

$$\int_{-\infty}^{\infty} u(t)\, dt = d \tag{26}$$

The unit impulse function has unit area, whereas the unit pulse function has unit height.

The pulse sampling function is defined as

$$u_T(t) \triangleq \sum_{k=-\infty}^{\infty} u(t) \tag{27}$$

Since the pulse sampling function is periodic in time, it may be expanded in a Fourier series in t. Substituting $u_T(t)$ for p(t) in Equation (6),

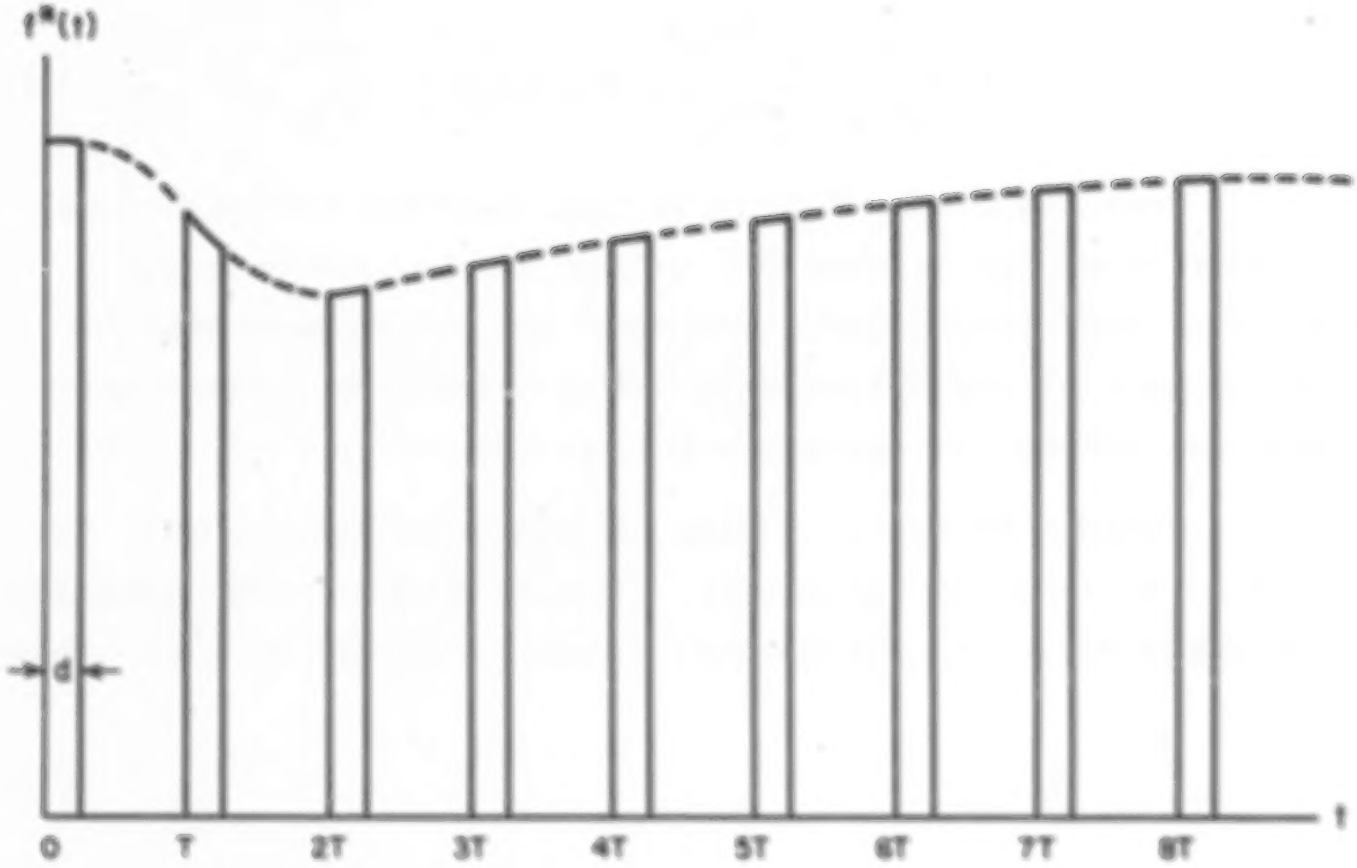
$$c_n = \frac{1}{T} \int_{-T/2}^{T/2} u_T(t)\, e^{-jn\omega_s t}\, dt \tag{28}$$

According to the defining relations in Equation (26), the only pulse which can occur in the interval of integration is the one which begins at the origin. Thus, Equation (28) may be reduced to

$$c_n = \frac{1}{T} \int_0^d e^{-jn\omega_s t}\, dt \tag{29}$$

$$= \frac{e^{-jn\omega_s t}}{-jn\omega_s T} \Bigg|_0^d$$

$$= \frac{1 - e^{-jn\omega_s d}}{jn\omega_s T} \tag{30}$$



SAMPLED SKIN RESISTANCE RESPONSE IN THE TIME DOMAIN
(Finite Sampling Duration)

FIGURE 7

Expressions for the sampled signal in the time and frequency domains are obtained by subetituting Equation (30) in Equations (8) and (10).

$$f^*(t) = \sum_{n=-\infty}^{\infty} \frac{1-e^{-jn\omega_s d}}{jn\omega_s T} f(t)\, e^{jn\omega_s t} \tag{31}$$

$$F^*(\omega) = \sum_{n=-\infty}^{\infty} \frac{1-e^{-jn\omega_s d}}{jn\omega_s T} F(\omega - n\omega_s) \tag{32}$$

Equations (31) and (32) are the basic equations for describing a signal after it has been sampled by a realistic sampler with sampling duration d. The characteristics of sampled data become more apparent when Equations (31) and (32) are expressed in terms of their trigonometric equivalents, and when the summation is taken only over $n = 1, 2, \ldots, \infty$.

Consider first the alternative expression for Equation (31). The case of $n = 0$ is evaluated separately. Since the term under the summation is not defined for $n = 0$, it is necessary to apply Lhopital's theorem. Then, for $n = 0$

$$c_o = \frac{d}{T} \tag{33}$$

Further, by expanding Equation (31), then combining terms,

$$f^*(t) = \frac{d}{T} f(t) + \sum_{n=1}^{\infty} \frac{\left[e^{jn\omega_s t} - e^{-jn\omega_s t}\right] - \left[e^{jn\omega_s (t-d)} - e^{-jn\omega_s (t-d)}\right]}{jn\omega_s T} f(t)$$

$$= \frac{d}{T} f(t) + \sum_{n=1}^{\infty} \frac{2\left[\sin n\omega_s t - \sin n\omega_s (t-d)\right]}{n\omega_s T} f(t) \tag{34}$$

By the use of trigonometric identities, it can be shown that Equation (34) can be reduced to

$$f^*(t) = \frac{d}{T} f(t) + \frac{2}{T} \sum_{n=1}^{\infty} \frac{2 \sin \frac{n\omega_s d}{2} \cos\left(n\omega_s t - \frac{n\omega_s d}{2}\right)}{n\omega_s} f(t)$$

$$= \frac{d}{T} f(t) + \frac{2d}{T} \sum_{n=1}^{\infty} \frac{\sin \frac{n\pi d}{T}}{\frac{n\pi d}{T}} f(t) \cos n\omega_s (t - \frac{d}{2}) \qquad (35)$$

Consider now the alternative expression for Equation (32). Again, the evaluation of Equation (32) for $n = 0$ is implied by Equation (33). Then,

$$F^*(\omega) = \frac{d}{T} F(\omega) + \sum_{n=-1}^{\infty} \frac{e^{jn\omega_s d} - e^{-jn\omega_s d}}{jn\omega_s T} F(\omega \pm n\omega_s)$$

$$= \frac{d}{T} F(\omega) + \sum_{n=1}^{\infty} \frac{2 \sin n\omega_s d}{n\omega_s T} F(\omega \pm n\omega_s) \qquad (36)$$

Again by the use of trigonometric identities, it can be shown that Equation (36) can be reduced to

$$F^*(\omega) = \frac{d}{T} F(\omega) + \frac{2d}{T} \sum_{n=1}^{\infty} \frac{\sin \frac{n\omega_s d}{2}}{\frac{n\omega_s d}{2}} F(\omega \pm n\omega_s) \cos \frac{n\omega_s d}{2}$$

$$= \frac{d}{T} F(\omega) + \frac{2d}{T} \sum_{n=1}^{\infty} \frac{\sin \frac{n\pi d}{T}}{\frac{n\pi d}{T}} F(\omega \pm n\omega_s) \cos \frac{n\omega_s d}{2} \qquad (37)$$

In the previous section which assumed an infinitesimal sampling duration, three characteristics of the sampled signal were discussed. These same three characteristics will again be discussed on the basis of Equations (35) and (37), which reflect a finite sampling duration.

First, the sampled signal is attenuated with respect to the pre-sampled signal, but again this is of little interest.

Second, $f^*(t)$, like $f(t)$, is a real function of time, whereas $F^*(\omega)$, like $F(\omega)$, is a complex function of frequency. Thus, $F^*(\omega)$ may be written

as an amplitude $|F^*(\omega)|$ and a phase angle, either one of which may be plotted against ω.

Third, $F^*(\omega)$ contains an infinite number of spectra, one at the origin, and the others at multiples of the sampling frequency. These harmonics occur with decreasing amplitude, with the nth harmonic attenuated by

$$\frac{\sin \frac{n\pi d}{T}}{\frac{n\pi d}{T}} \tag{38}$$

which diminishes rapidly as n increases. The sampled signal is reduced to zero at frequencies where $\sin \frac{n\pi d}{T} = 0$, which occurs whenever $\frac{n\pi d}{T} = \pi$. Complete attenuation first occurs at

$$\omega = \frac{2\pi}{d} \tag{39}$$

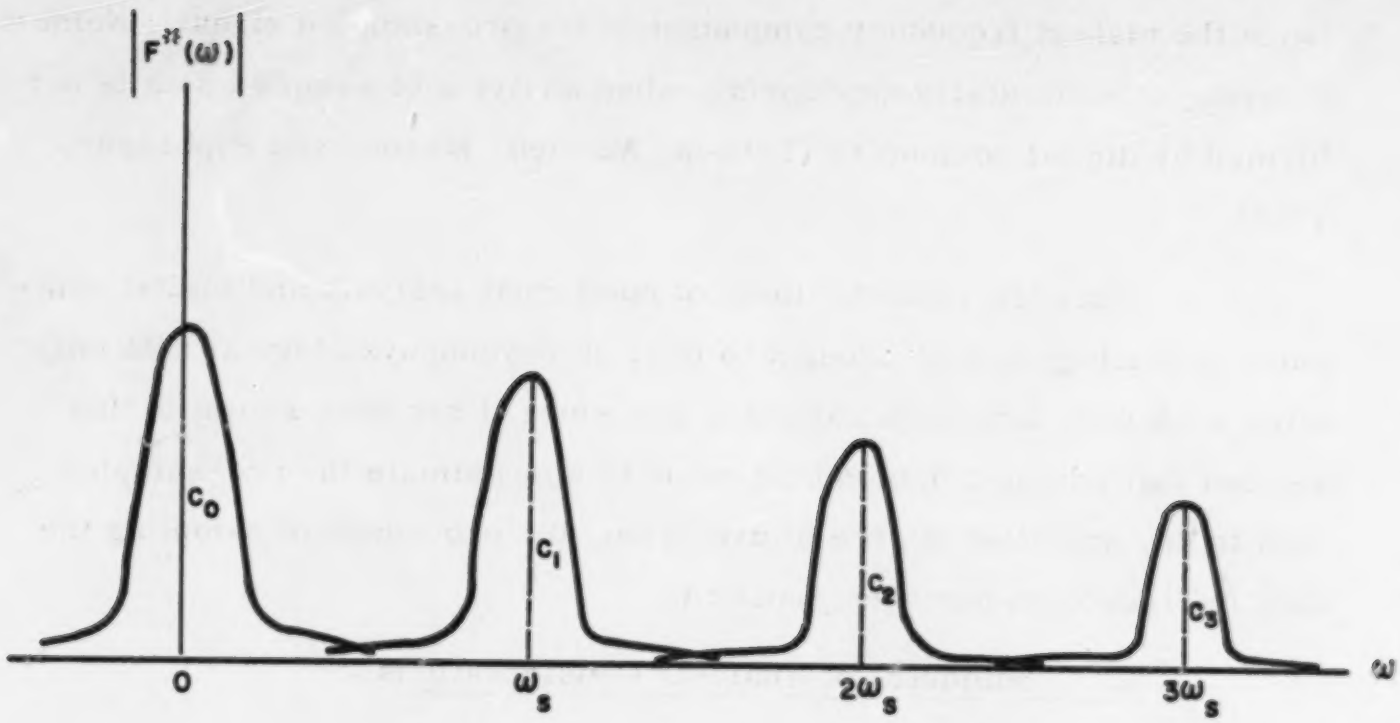
Complete attenuation also occurs at multiples of this particular frequency.

The attenuation of frequencies other than at multiples of the sampling frequency is derived from Equation (38) by replacing $n\omega_s$ by the continuous variable ω. Thus, the attenuation envelop is given by

$$\frac{\left|\sin \frac{\omega d}{2}\right|}{\frac{\omega d}{2}} \tag{40}$$

The sampled signal in the frequency domain is shown in Figure 8, again for the same skin resistance response. Aside from the attenuation, the representation is identical to that of Figure 6. For any given harmonic n, the nodal amplitude is equal to c_n.

The primary component centered on the origin is the desired signal, and some method must be found to reject the complementary components (sidebands). For crude applications this might be achieved by increasing d, but this has the disadvantage of attenuating not only the complementary components but also the primary component to some extent.



SAMPLED SKIN RESISTANCE RESPONSE IN THE FREQUENCY DOMAIN
(Finite Sampling Duration)

FIGURE 8

A more satisfactory solution is to pass the sampled data through a sampled-data (discrete) filter (Salzar, 1961). An unusual feature of sampled signals is that the signal spectrum can be recovered by a linear filter (Ragazzini and Franklin, 1958). An ideal filter of this type would be a low-pass filter whose bandwidth extends to half the sampling frequency; such a filter could recover the signal completely if the sampling rate were twice the highest frequency component in the pre-sampled signal. Numerical filtering is particularly appropriate when analysis of sampled data is performed by digital computers (Taback, Marden, Mason, and Pipberger, 1959).

Since the powerful tools of numerical analysis and digital computer technology can be brought to bear on psychophysiological data only after such data have been sampled, and since it has been shown in this section that sampled data can be made to approximate the pre-sampled data to any specified degree of precision, the procedure of sampling the data in classroom has been justified.

3. Summary of Analysis Considerations

Before turning to the next section on analysis implementation, the material in this long section on analysis considerations will be summarized.

This section assumed that a signal of the type described under measurement implementation would be sampled in the classroom. Sampling would increase the number of recording channels (the number of students times the number of channels/student) which a given recorder could handle. However, the pre-sampled data are different from the sampled data. Further, while it is the former which is of interest, it is the latter which is analyzed. Therefore, before analysis of the sampled data could proceed on a rational basis, it was necessary to consider the relationship between the pre-sampled and the sampled signal.

The characteristics of the pre-sampled signal were described in terms of the Fourier transform pair of $f(t)$ - Equations (1) and (2) - the basic

equations which form the basis of this section on analysis considerations. These equations allow a signal in time to be represented in frequency, and vice versa. While both representations are mathematically equivalent, it is useful to represent a signal in both the time and frequency domains, for each representation makes a unique appeal to intuition.

The application of Equations (1) and (2) was indicated for two typical analyses; the first exists in the present study, and the second will probably become important in classroom research in the future. The first involved the skin resistance response, for which an explicit function was suggested. The second example involved the EEG, for which the correlation function and its transform, the spectral density function, were discussed in terms of objective analysis of EEG data.

The characteristics of the sampled signal were described for the case of a sampler with a constant sampling frequency ω_s, resulting in a constant sampling period T. Such a sampler was conceived of as a modulator which enabled the pre-sampled signal f(t) to modulate a sampling function p(t). The resultant sampled signal f*(t) could then be expressed as $f^*(t) = f(t)\, p(t)$.

Since p(t) is periodic in time, it was represented as a Fourier series, expressed in its exponential form. The pair of equations - the Fourier coefficients c_n as a function of p(t) and vice versa - were shown to be a special case of the Fourier transform pair.

Two sampling functions were described: the impulse sampling function based on the unit impulse function, and the pulse sampling function based on the unit pulse function. The first represented an ideal sampler with an infinitesimal sampling duration, while the second represented a realistic sampler with a finite sampling duration. These two cases were discussed under separate subsections.

The sampled signal resulting from a sampler with an infinitesimal sampling duration was shown to possess a periodic frequency representation

- actually an infinite number of spectra located at multiples of the sampling frequency, with each spectrum equal to the (attenuated) frequency spectrum of the pre-sampled signal.

The sampled signal resulting from a sampler with a finite sampling duration was shown to possess a frequency representation similar to that described above, but with the spectra increasingly attenuated for increasing frequency.

For either of these frequency representations, the spectrum centered on the origin represents the desired signal, the remaining spectra being complementary components (sidebands). It was shown that these undesired components could be filtered out if the sampling frequency were sufficiently high (ideally only twice the highest frequency component in the pre-sampled signal). Graphical representations were given for the skin resistance response both before and after sampling this signal in the classroom.

B. ANALYSIS IMPLEMENTATION

Based on the previous analysis considerations, a library of computer programs was developed to analyze the data recorded in the classroom. Most programs were written specifically for this study, but in some cases, existing programs were modified for this study.

Without going into detail, this section will describe the functions of these programs. Only those programs will be described which operate with the IBM 7090. These programs fall into two broad classes: data conditioning programs and data analysis programs.

1. Data Conditioning

Before analysis is begun, the data are subjected to five preliminary data-conditioning operations.

First, the data are unpacked so that each data value occupies one word. The data were originally packed by a SWAC routine, 3 values per word, in order to achieve more efficient data transmission from one machine

to the next. Analysis, however, would proceed more efficiently with one value/word. This first subroutine is written in FAP; all others are written in FORTRAN.

Second, the unpacked data may be collated by student and by variable. During recording, the 180 channels may have carried information on 180 students with one variable/student, or 60 students with three variables/student, or any other combination which does not exceed 180. Further, more than one channel may have been allocated to one student for one variable in order to raise the sampling frequency. In general, the recorded data are mixed in the sense that adjacent values do not necessarily pertain to the same student or to the same variable. Yet most analyses, particularly ipsative analyses, are more efficient when the data for each student-variable unit are stored in consecutive cells. For this reason, the mixed data are separated, collated by student-variable units, and written as student-variable units on a single tape. Collating the data for a given student-variable unit has been made quite efficient by writing the first half of the mixed data on one intermediate tape, the second half on a second intermediate tape. Since a given student-variable unit will contain data values on both tapes, one tape can be rewinding while the desired data values are being read from the other tape.

Third, the data may be corrected for possible wild points. Wild points are detected by comparing the difference between the (k+1)st value and kth value against a criterion value, which is input as a parameter and remains constant throughout the run. When the criterion value is exceeded, the (k+1)st value is made equal to the kth value.

Fourth, the data may be filtered so as to attentuate frequencies outside the frequency band of interest. Some type of filtering is necessary to remove the replicated spectra generated by the sampling process, as was described in the previous section. The current method of filtering, a crude but simple method, consists of replacing the kth point by an average of this point and the p adjacent points (p/2 points on each side of the kth point). The time spanned by these (p+1) points is pT, where T is the

sampling period. This filtering procedure has an effect similar to that of a sampler with a sampling duration of d = pT. Thus, this averaging procedure results in an attenuation of the data representation in the frequency domain, as given by Equation (40). For instance, if p=2 and $T = \frac{1}{24}$, then $d = pT = \frac{1}{12}$, and Equation (40) vanishes for $\omega = 2\pi(12)$, which is the frequency at which 60 cps interference is projected from frequency spectra folded about $-2\omega_s$ and $3\omega_s$. Of course, attenuation also occurs in the frequency range of interest. For skin resistance, this range is likely to be restricted to 0 to 1 cps, and in this range maximum error will occur at 1 cps. For the example just given, with p = 2, the error at 1 cps is only 1%.

Fifth, the number of data values may be reduced if it turns out that the sampling frequency was unnecessarily high. The data reduction subroutine allows the difference between adjacent data values to be compared against a criterion value, which is input as a parameter. If all differences are less than the criterion value, every other value is eliminated, and the process is repeated.

The five subroutines which perform these operations, as well as all the following subroutines, are under the control of an executive routine. Except for the data unpacking subroutine, all subroutines are optional, and an executive control card allows one to select those subroutines to be used for a given run.

2. Data Analysis

Analyses are performed in the time and frequency domains, and in each domain, analyses are performed on a unit of data and between these units of data. For ipsative analyses the unit of data would be one student-variable unit, while for normative analyses the unit of data would be one variable over all students, or over a selected subsample.

Time domain analyses for any unit of data include the mean, variance, derivative at each instant in time that the original continuous signal was sampled, and the auto-correlation for any number of lags; time domain analyses between any two units of data include the covariance and

the cross-correlation for any number of lags of either unit. Frequency domain analyses for any unit of data include the spectral density; frequency domain analyses for any two units of data include the cross-spectral density, the phase angle between the two time series, the amplitude of the transfer function from either unit of data to the other, and the coherence between units.

PRECEDING PAGE BLANK-NOT FILMED

IV. A TRIAL STUDY

The primary objective of this research was to design and implement a system for the measurement and analysis of physiological response of students viewing a film in the classroom. A secondary objective was to expose the system to a simple trial study. The study which was undertaken was sufficient to confirm the adequacy of the system. This part of the report will describe that study.

A. PROBLEM

The galvanic skin response (GSR) has been used as an indicator of student interaction with film material. In Part I of this report, mention was made of the Dysinger and Ruckmick study (1933), in which the relation between film-mediated GSR and verbal report was investigated. Similarly, the Humphrey study (1950) explored the relation between film-mediated GSR and verbal response to a standardized test. These studies are representative of the many studies which involve the investigation of the relation between GSR and some verbal measure.

Generally, the primary interest is not in the verbal measure itself but in some socially meaningful behavior with which the verbal measure is presumably correlated. In such cases, it is more satisfying, though generally more difficult, to investigate the direct relation between GSR and the behavior of interest.

The present study investigated the direct relation between the skin resistance response and traffic accident involvement.

B. METHOD

A film, prepared for this study, was viewed by students in a typical classroom situation. The motion picture was short and simple, and consisted of one clear, blank frame. This film was preceded by 200 feet of opaque leader, and followed by the same material. The projector lamp was on during the entire projection, but no light was transmitted to the screen except during the time the clear frame was in the aperture. The effect was that of 5 minutes of darkness, a flash of light, then darkness again.

The subjects consisted of 24 upper-division college students, seven females and 17 males. The subjects were exposed one at a time to the experimental condition described in the paragraph above. He was asked to take a seat in the middle of the classroom and to place on his fingertips a pair of electrodes. He was offered a more appropriate size if he reported that the first size failed to result in a firm, yet comfortable, fit. He was told to relax, and to watch the screen even though it would be some time before material would appear on the screen.

The student's skin resistance was recorded according to the procedure described in Part II. Only 1 of the 180 channels recorded the signal, while each of the remaining 179 channels, in effect, recorded a zero signal. Each subject was exposed to about 3 microamps of current, but since each female subject chose the smaller area electrode, the current density for females was nearly twice as high. However, since the current density for both sexes was minimal, the difference in current density was ignored in this trial study.

After the recording was finished and the classroom lights turned on, the student was asked to fill out a form requesting (1) his driver's license number, and (2) his estimate of the number of miles he had driven each year for the previous three years. His driver's license number was used to obtain a report from the California Department of Motor Vehicles. Interest focussed on whether the subject's official driving record indicated involvement in at least one traffic accident during the three year period.

The raw data consisted of skin resistance values in ohms, one value per film frame. Since the 7 female subjects selected to use the smaller area electrodes, it was necessary to multiply their resistance values of the ratio of the smaller to the larger electrode area (described in Part II) in order to achieve a common basis for comparison of female and male resistance values. The term "resistance values" will be used for both sexes, it being understood that the term implies adjusted values for females.

The data for each subject consisted of 480 resistance values recorded in synchronism with 480 consecutive frames (20 seconds), with 240

of these values recorded during the 10-second period preceding the light flash, and 240 values recorded during the 10-second period following the light flash. These two periods will be referred to as the pre-stimulus and post-stimulus periods.

Various measures were computed for each subject from his skin resistance values. These measures are listed under the following three categories.

1. Absolute Measures

   a. Mean of resistance values for the 20-second period.

   b. Mean of resistance values for the pre-stimulus period (often referred to as the basal resistance.)

   c. Mean of resistance values for the post-stimulus period.

   d. Variance in resistance values for the 20-second period.

   e. Variance in resistance values for the pre-stimulus period.

   f. Variance in resistance values for the post-stimulus period.

   g. Minimum resistance value for the post-stimulus period.

   h. Time between stimulus presentation and occurrence of minimum resistance value.

   i. Time between stimulus presentation and occurrence of maximum rate of decrease in resistance values.

2. Difference Measures

   a. Maximum difference between two resistance values.

   b. Difference between 1b and 1c.

   c. Difference between 1b and minimum post-stimulus resistance value.

   d. Difference between 1e and 1f.

3. Ratio Measures

   a. Ratio of 2c to 1b (a ratio which approximates the GSR as this term is used by many investigators)

   b. Maximum rate of decrease in resistance values for the post-stimulus period.

For each of these 15 measures, a two-by-two frequency table was constructed. One dichotomized dimension was one of these 15 measures (below median vs. above median), and the other dichotomized dimension was recorded accidents during the preceding three years (no vs. yes). The probability of the obtained frequency distribution (plus all other distributions more extreme) was calculated for each of these 15 tables.

C. RESULTS

None of the 15 probabilities approached a statistically significant level. However, an examination of the computer-plotted resistance values revealed that 7 subjects showed an increase in resistance values almost immediately after the stimulus. The frequencies for the dichotomized measure of an increase in resistance immediately after the stimulus (no vs. yes) are shown in Table 1.

TABLE 1

FLASH-MEDIATED INCREASE IN RESISTANCE IN RELATION TO RECORDED ACCIDENTS

		Resistance Increase		
		no	yes	
Recorded Accidents	yes	1	3	4
	no	16	4	20
		17	7	

Thus, 4 of the 24 subjects had at least one recorded accident during the three-year period preceding the study, and 3 of these 4 subjects showed an increase in resistance.

The probability of the distribution in Table 1 (plus the probability of the additional distribution more extreme) was .059. Since the expected entries were so low, this probability was computed directly (Kendall, 1951) rather than determined indirectly from a Yates-corrected chi-square.

D. DISCUSSION

The discovery that a skin resistance measure is related to recorded accidents near the .05 level, is not of particular interest by itself. To begin with, a chance relationship at this probability level might be expected on the basis of the number of probabilities computed. Further, the computed probability does not in itself support the hypothesis that an increase in skin resistance is related to traffic accident involvement, for such an hypothesis was not formulated before the study was begun.

However, the relationship begins to take on interest when it is interpreted in the light of other facts. First, an increase in skin resistance following a stimulus has not been generally noted in the literature. This may be due to the fact that most previous studies involving skin resistance have utilized relatively insensitive graphic recorders; the technique used in the present study has at least 10 times the sensitivity. The increase in skin resistance is not nearly as large as the conventionally-investigated decrease. The detection of the increase would be difficult from a graphic recorder whose sensitivity had been adjusted to record a decrease in skin resistance.

Second, the increase in skin resistance, if it occurs at all, occurs about 100-200 milliseconds after the stimulus (the typical decrease in resistance occurs about 1-2 seconds after the stimulus). The latency of the resistance increase is of the same order of magnitude as a reflex involving the hand. It is not inconceivable that the skin resistance response may involve two related mechanisms - a shorter latency neural mechanism, and a longer latency biochemical mechanism.

Third, despite a substantial range in the rate of resistance increase among the 7 subjects showing such an increase, the rate of increase for any given subject approximated his rate of decrease. This equivalence in lability cannot be attributed to the pre-stimulus level; that is, a high positive rate of change is associated with a high negative rate of change, but neither is necessarily associated with a high pre-stimulus resistance level.

Fourth, a previous study (Levonian, Case, and Gregory, 1963) revealed that drivers with faster simple reflexes are involved in more accidents. The present study suggests that drivers showing an increase in skin resistance are also involved in more accidents. These two results suggest that the latency of a reflex to a stimulus may be correlated with the change in skin resistance which may occur during a period approximately equal to the latency period.

REFERENCES

1. Aseltine, John A. Transform Method in Linear System Analysis. New York. McGraw-Hill, 1958.

2. Auld, Frank Jr., Dreyer, Harry W., and Dollard, John. Measurement of Electrical Skin Resistance During Interviews. Psychological Reports, 1958, 4, 11-15.

3. Blank, Irwin H., and Finesinger, Jacob E. Electrical Resistance of the Skin. Archives of Neurology and Psychiatry, 1946, 56, 544-557.

4. Dirac, P.A.M. The Principles of Quantum Mechanics. Second edition. New York: Oxford University Press, 1935.

5. Dysinger, W.S., and Ruckmick, C.S. The Emotional Responses of Children to the Motion Picture Situation. New York: MacMillan, 1933.

6. Grings, W.W. Methodological Considerations Underlying Electrodermal Measurement. Journal of Psychology, 1953, 35, 271-282.

7. Humphrey, J. H. Emotion Reactions to Abstract Motion on Film. Journal of the University Film Producers Association, 1950, 3, 11-12.

8. Kendall, Maurice G. The Advanced Theory of Statistics. Fifth edition, Vol. 1. London: Charles Griffin, 1952.

9. Kleitman, N. The Effect of Motion Pictures on Body Temperature. Science, 1945, 101, 507-508.

10. Levonian, Edward. Measurement of Physiological Response to Film. Psychophysiology Newsletter, 1962, 8, 16-23.

11. Levonian, Edward, Case, Harry W., and Gregory Raymond. Prediction of Recorded Accidents and Violations Using Non-driving Predictors. Highway Research Board Proceedings, 1963, 42. In press.

12. Lykken, D.T. Properties of Electrodes used in Electrodermal Measurement. Journal of Comparative and Physiological Psychology, 1959, 52, 629-634.

13. Oliver, B.M., Pierce, J.R., and Shannon, C.E. The Philosophy of Pulse Code Modulation. Proceedings of the IRE, 1948, 36, 1324-1331.

14. Ragazzini, John R., and Franklin, Gene F. Sampled-data Control Systems. New York: McGraw-Hill, 1958.

15. Renshaw, S. Sleep Motility as an Index of Motion Picture Influence. Journal of Educational Sociology, 1932, 6, 226-230.

16. Renshaw, S., Miller, V.L., and Marquis, D.P. Children's Sleep. New York: MacMillan, 1932.

17. Ruckmick, C.A. How do Motion Pictures Affect the Attitudes and Emotions of Children? The Galvanic Technique Applied to the Motion Picture Situation. Journal of Educational Sociology, 1932, 6, 210-216.

18. Salzar, John M. Sampled-data Theory. In Leondes, Cornelius T. (Ed.), Computer Control Systems Technology. New York: McGraw-Hill, 1961.

19. Savant, C. J., Jr. Fundamentals of the Laplace Transformation. New York: McGraw-Hill, 1962.

20. Taback, L., Marden E., Mason, H. L., and Pipberger, H. V. Digital Recording of Electrocardiographic Data for Analysis by a Digital Computer. IRE Transactions on Medical Electronics, 1959, 167-171.

21. Tou, Julius T. Digital and Sampled-data Control Systems. New York: McGraw-Hill, 1959.